2.3 Effect of Barrier and Elevation

The adopted convergence PMP is for 1000 mb (100 kPa) or sea level. For locations at higher elevations or to the lee of mountain barriers, the 1000-mb (100-kPa) convergence PMP must be decreased. This is accomplished by reductions for barrier and elevation.

2.3.1 Effective Barrier and Elevation Map

During strong inflow of saturated or near saturated air, moisture is depleted on windward slopes by the higher elevations. Moisture is depleted for areas to the lee of upwind barriers by the effect of the barrier.

Elevations used in this study were based on smoothed elevation contours of a 1:1,000,000 scale topographic map. The smoothing moved the actual terrain elevation slightly upwind. This "effective" elevation, as differentiated from the actual elevation, provided for greater moisture into a region because precipitation particles can be carried along by the wind to higher elevations.

The "effective" barrier for the lee areas was determined from the height of the upwind barrier. These effective barriers may differ from the maximum elevation of the barrier since allowance was made for moisture flow through substantial breaks in the ridgeline.

Inflows from southwest through south-southeast were of prime importance in deriving the effective barrier and effective elevation chart for a large portion of the Southwestern States. Winds from westerly to northwesterly directions were involved near the northwest corner of the region. A reasonable tie-in was maintained with the effective barrier and elevation charts of studies for adjoining areas. Also, inflow into southwestern Wyoming and northeastern Utah from the east to northeast resulted from the prototype storm for this portion of the study region. This is consistent with extreme rains to the east of the Continental Divide caused by easterly flow in late spring storms.

With some variability permitted in the direction of moist inflow, isolated mountains and ridges less than 10 miles (16 km) long (measured at the base relative to the wind direction) are not effective in reducing moisture. The effective barriers were in many instances phased out, downwind, at a distance about 1 to 1.5 times their length, implicitly allowing recharge of moisture behind such obstacles. The amount of recharge is similar to that of bordering generalized reports (HMR Nos. 36 and 43). Recharge toned down or eliminated effects of ridges somewhat longer than the initial 10-mi (16-km) criterion. Figure 2.17 shows the combined barrier/elevation map for the for the Southwest.

2.3.2 Reduction for Effective Barrier and Elevation

Variation of nonorographic PMP with barrier height and elevation has been made proportional to the variation with elevation of precipitable water in a saturated column. It is the same as that used for convergence PMP in HMR No. 36 for California and for some of the variation in HMR No. 43 for the

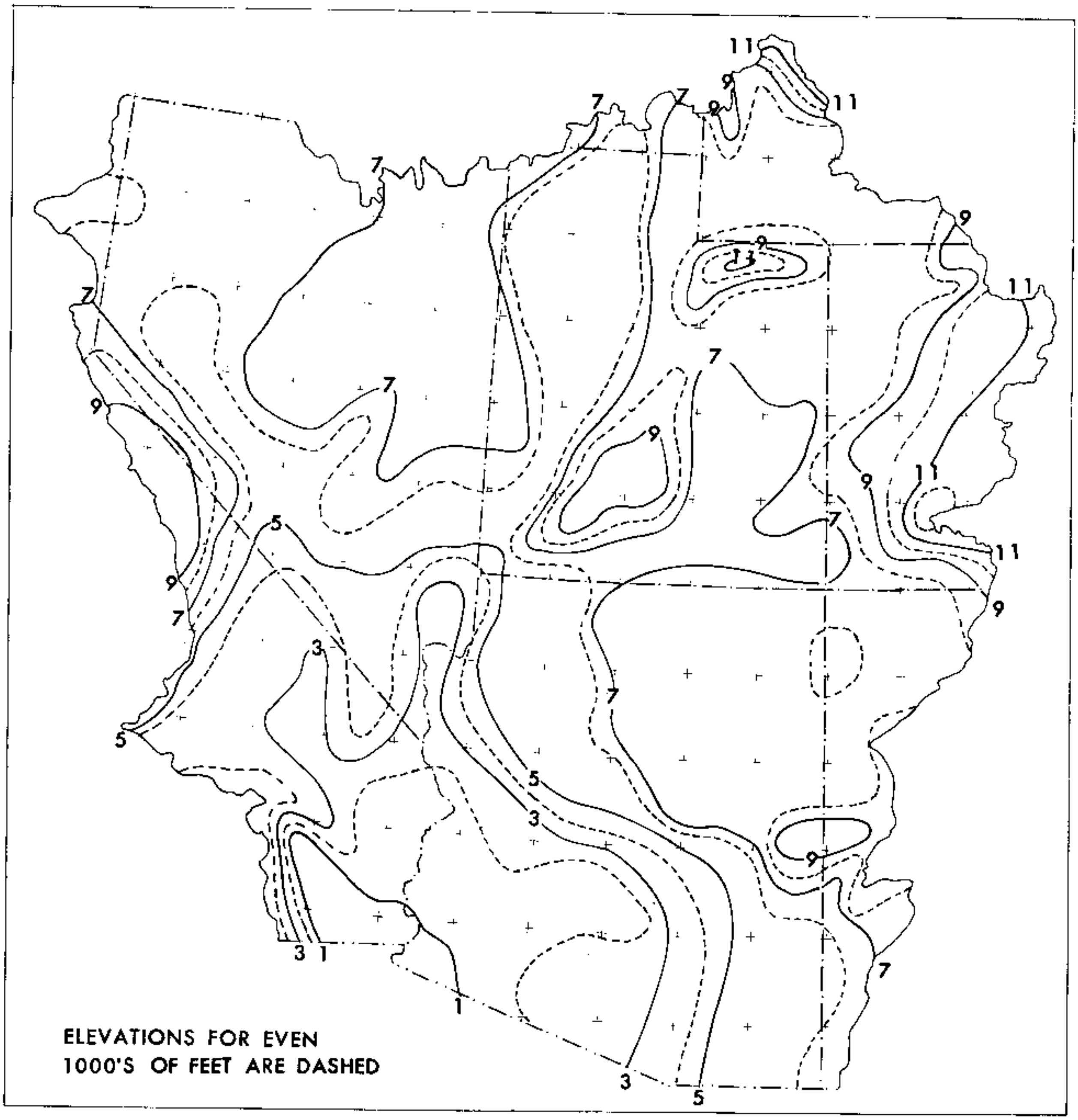


Figure 2.17.--Effective barrier and elevation heights (1000's of feet) for Southwestern States.

Columbia River drainage. The adopted variation with elevation, which is proportional to the variation in precipitable water, is consistent with the method used for moisture-maximizing the greatest observed least-orographic rains for guidance in setting the level of 1000-mb (100-kPa) convergence PMP.

The maximum 12-hr persisting 1000-mb (100-kPa) dew points for August general storms (Schwarz and Hansen 1978) of 73° (23°C) were used for determining the percent reduction due to effective barriers and elevations. The August dew points tend to give less reduction than winter dew points. High-elevation rainfall would be unreasonably reduced if winter dew points were used, particularly because the use of a single moisture chart does not allow for the high wind and therefore higher rainfall capability at the higher elevation in the cool season.

Figure 2.18 shows the reduction (in percent) of 1000-mb (100-kPa) convergence PMP for effective barrier and elevation over the Southwestern States. There is agreement between the patterns shown in figures 2.17 (barrier/elevation) and 2.18 (reduction of 1000-mb (100-kPa) convergence PMP) with one exception. Figure 2.18 contains a large area of 45% reduction in northeastern Arizona, to the lee (northeast) of the Mogollon Rim. A continuous approximate 8,000-ft (2,440-m) barrier does not exist to support the 45% feature directly. We believe this factor is justified, since the effect of downslope motion behind the major barrier is to produce additional drying of the air which is equivalent to a higher effective barrier. Further downwind, the 45% reduction line has been closed off to indicate the gradual influence of recharge of moisture below 8,000 ft (2,440 m).

When using figure 2.18 to determine a percent of convergence PMP for a specific basin, interpolate between the isopleths. However, for locations that lie within closed contours or at the end of gradients, (within the 95% contour in southern California, and within the 50% contour in north-central Nevada, for example), the correct value is that of the last identified contour, i.e., do not extrapolate.

2.4 Depth-Duration Variation

The 24-hr mid-month convergence PMP values can be extended to other durations through application of rainfall depth-duration relationships. Durations between 6 and 72 hours are required. Relationships were developed from 6/24-hr, 48/24-hr and 72/24-hr ratios of rainfall in selected severe storms and from maximum rainfalls of record at recorder stations. Seasonal and regional variations of depth-duration relations are given.

2.4.1 Data

Hourly precipitation data for up to 25 years (1948-72) were available on magnetic tapes for recorder stations listed in table 2.4. These stations are located in the least-orographic regions shown in figure 2.1. Stations A, B, C, D, and F in table 2.4 are geographically close to stations 3, 10, 11, 13, and 23, respectively, in table 2.2. An additional station at Baker, California (station E in table 2.4) was included in the southern Nevada subregion. Although some of these stations (A to F) had records exceeding 20 years, only

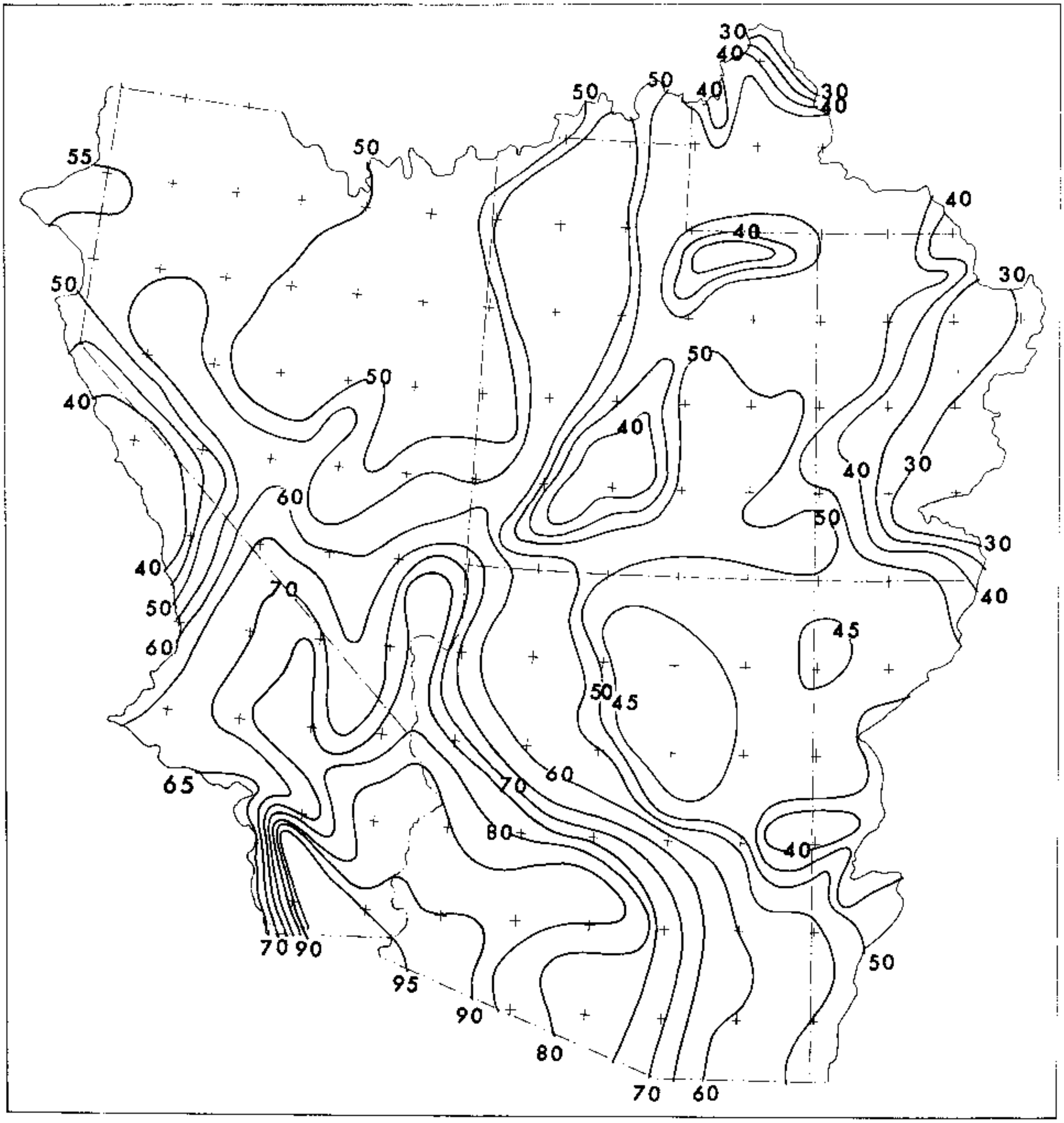


Figure 2.18.--Percent of 1000-mb (100-kPa) convergence PMP resulting from effective elevation and barrier considerations. Isolines drawn for every five percent.

Table 2.4.--Stations within least-orographic regions for which hourly precipitation data were available for the period 1948 through 1972.

	Station	Latitude	Longitude	Elevation ft	(m)
	Southwest Arizona				
	Ajo, Ariz.	33°22	112°52	1763	(537)
A*	Casa Grande Ruins, Ariz.	33°00	110°32	1419	(433)
	Phoenix, Ariz.	33°28	112°04	1083	(330)
	Yuma, Ariz.	32°44	114°36	138	(42)
	Blythe, Calif.	33°37	114°36	268	(82)
B	El Centro, Calif.	32°46	115°34	- 37	(- 11)
	Iron Mt., Calif.	34°08	115°08	922	(281)
C	Thermal, Calif.	33°38	116°10	- 112	(- 34)
	Northeast Arizona				
D	Keems Canyon, Ariz.	35°49	110°12	6205	(1893)
	Winslow, Ariz.	35°01	110°44	4880	(1487)
	Green River, Utah	39°00	110°09	4087	(1246)
	Hanksville, Utah	38°25	110°41	4456	(1358)
	Crownpoint, N. Mex.	35°40	108°13	6978	(2128)
	Farmington, N. Mex.	36°43	108°12	5300	(1615)
	Western Utah				
F	Delta, Utah	39°20	112°35	4626	(1410)
	Dugway, Utah	40°10	113°00	4359	(1329)
	Enterprise B. Jct., Utah	37°43	113°39	5220	(1598)
	Milford, Utah	38°25	113°01	5029	(1535)
	Wendover, Utah	40°44	114°02	4239	(1292)
	Malad, Idaho	42°11	112°16	4420	(1347)
	Southern Nevada				
	Beatty, Nev.	36°54	116°45	3314	(1010)
	Caliente, Nev.	37°37	114°31	4402	(1342)
	Las Vegas, Nev.	36°10	115°09	2006	(611)
	Searchlight, Nev.	35°28	114°55	3540	(1079)
E	Baker, Calif.	35°16	116°04	940	(287)
	Needles, Calif.	34°46	114°38	913	(278)
	Northwest Nevada				
	Elko, Nev.	40°50	115°47	5075	(1548)
	Lovelock, Nev.	40°12	118°28	3977	(1212)
	McDermitt, Nev.	42°00	117°43	4427	(1349)
	Winnemucca, Nev.	40°54	117°48	4314	(1315)

*Locators in figure 2.1.

the longer record station was used in the studies for determining the magnitude and regional and seasonal variation of convergence PMP.

Additional data were sought from major storms of record for which there were large rainfalls in least-orographic regions. Almost all major storms in the Southwest have their centers in orographic regions; thus, it is difficult to obtain large amounts (more than one inch in 24 hours) in least-orographic regions. Data from the August 1951 and the northern center of the September 1970 storms along with seven lesser nonsummer storms were considered for guidance in establishing the seasonal variation of durational relations. The latter storms are listed in table 2.5.

Table 2.5.--Nonsummer storms in the Southwest and the number of stations with relatively large rainfalls in least-orographic regions, used in duration analysis of convergence PMP.

Date	No. of stations	Location
Dec. 14-17, 1908	4	W. Cent. Arizona
Dec. 17-24, 1914	6	S. Arizona
Jan. 14-20, 1916	5	S. Arizona
Feb. 01-07, 1905	5	SE Calif., S. Ariz.
Feb. 10-22, 1927	3	S. Utah
Mar. 11-17, 1941	3	SE Calif., S. Ariz.
Apr. 05-10, 1926	2	S. Arizona

2.4.2 Depth-Duration Relation

A depth-duration relation of PMP for an area size indicates the relationship between PMP values for various durations. It can be specified by a smooth curve of duration vs. depth (either in inches or percent of the value for a selected duration) or mathematically by ratios of the depths for various durations to that say of 24 hours. A PMP depth-duration relation is based on the concept that the average intensity of rainfall decreases with increasing duration. This concept is analogous to that in depth-area relations of PMP in which precipitation decreases with increasing area size. It might be well to point out that a depth-duration relation of PMP does not specify the time sequence in which incremental rain will fall. A smooth depth-duration relation can be quite well defined by the 6/24- and 72/24-hr ratios of rainfall.

Some regional PMP studies have used one depth-duration relation for the entire region. From preliminary examination of 6/24-hr ratios of rainfall, it was apparent that seasonal and regional variations precluded use of a single relation for the Southwestern States.

As an alternative, a concept of a family of smooth depth-duration relations was envisioned that would cover the range of probable relations required. When expressed in percent of the 24-hr amount, the concept of a smooth family of curves that require a continually decreasing rate of rainfall intensity involves an inverse relationship: Where the short-duration value is high, the long-duration value with which it is associated is low, and vice versa. In effect, this implies that high 6/24-hr ratios relate to low 72/24-hr ratios, and that low 6/24-hr ratios relate to high 72/24-hr ratios.

A tendency to support the inverse relation can be seen in the data plotted in figure 2.19. These ratios are selected within-storm (paired 6/24- and 72/24-hr ratios from the same storm) values from the stations in table 2.4. All storms were used where the 24-hr amount equalled or exceeded 1.0 inch (25 mm). To aid in understanding seasonal variations the data were stratified according to winter (Jan. and Feb.) and summer (Jul. and Aug.) months. An attempt was made to reduce the influence of thunderstorms by purging the data to eliminate 6/24-hr ratios greater than or equal to 0.90 and 72/24-hr ratios less than or equal to 1.10. An envelopment of the data in figure 2.19 supports an inverse relation. Similarly, a rough average through all the points, aside from the wide scatter, supports an inverse relation.

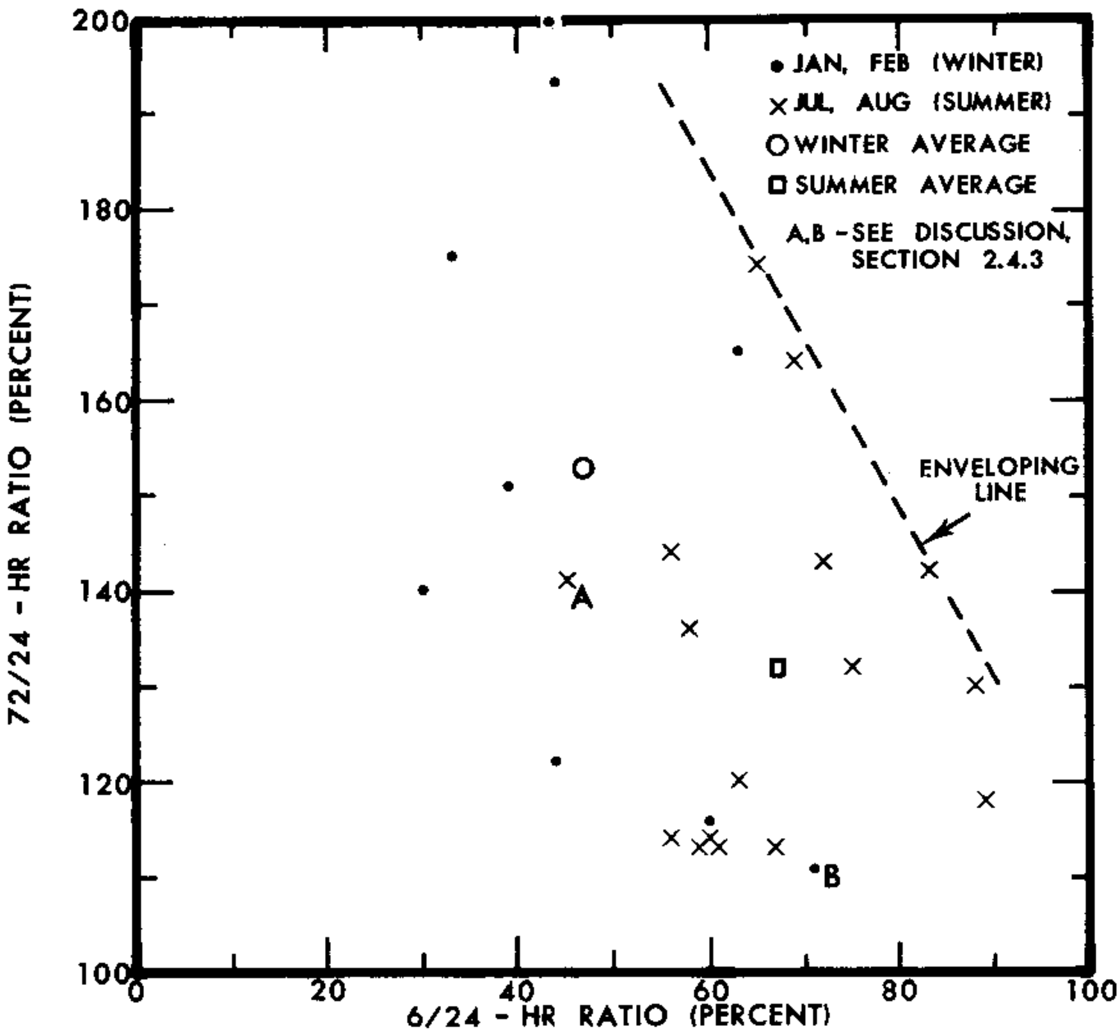


Figure 2.19.--Relation between 6/24-hr and 72/24-hr ratios for within-storm cases of 3 consecutive day rainfall for all stations listed in table 2.4 (see text for criteria for selection). Points identified as winter or summer.

A family of depth-duration curves that would cover the range required in the Southwest was then developed. First, a base depth-duration curve was established using all recorder data for least-orographic stations in the August 1951 and September 1970 storms. These storms are the closest to the prototype PMP storm for most of the Southwest. Averages of 6/24-, 12/24-, 18/24-, 48/24-, and 72/24-hr ratios are shown by the large dots in figure 2.20. The 72-hr dot is based solely on August 1951 data. A smooth line was drawn through these dots.

Next, we expanded this base depth-duration curve to a family of curves constrained by the limits:

a. Contant rainfall rate. A straight line from 0 to 100% at 24 hours to 300% at 72 hours.

b. All rain in the first instant, or 100% at all durations.

These two constraints are represented by the straight lines in figure 2.20. There is great flexibility in how to draw additional curves between these two lines. We selected 6/24-hr ratios at increments of 30, 40,..., 90% and drew smooth curves between 0 and 24 hours that were consistent with the curvature of the basic relation and somewhat symmetrical about a perpendicular bisector to the curves.

The 6 additional curves were then extended to 48 and 72 hours as smooth (not necessarily straight) lines. Further adjustments were made to the increments between curves beyond 24 hours in order to maintain a gradual increase (smooth gradient) in the increment between successive curves as the 72/24-hr ratios increased. The control for this gradient was the range in individual recorder durational curves for the stations used in the August 1951 and September 1970 storms. Although the family of curves in figure 2.20 suggests a broad range of 72/24-hr ratios, a much smaller range is applicable to the Southwest as discussed under seasonal and regional variations.

The PMP study for the Northwestern States, HMR No. 43, used a similar generalized set of depth-duration relations for convergence PMP. While not developed in the same manner as in the present study, the results are similar. Adopted smooth relations from the two studies are compared in figure 2.21.

2.4.3. Seasonal variation

It is to be expected that the 6/24-hr ratio should have a seasonal variation, i.e., because of greater convective activity ratios should be higher in summer than in winter.

In figure 2.19, a check was made of two points (labelled A and B) that appear to be extremes relative to the seasonal distribution of points indicated in this figure. Hourly precipitation records and synoptic weather analyses indicate that point A is the result of 3 days of isolated afternoon thundershowers. Thus, it is not representative of a general-storm summer rainfall. Point B results from one-day rainfall associated with a rapidly moving and dissipating low-latitude cold front with light post-frontal showers on the

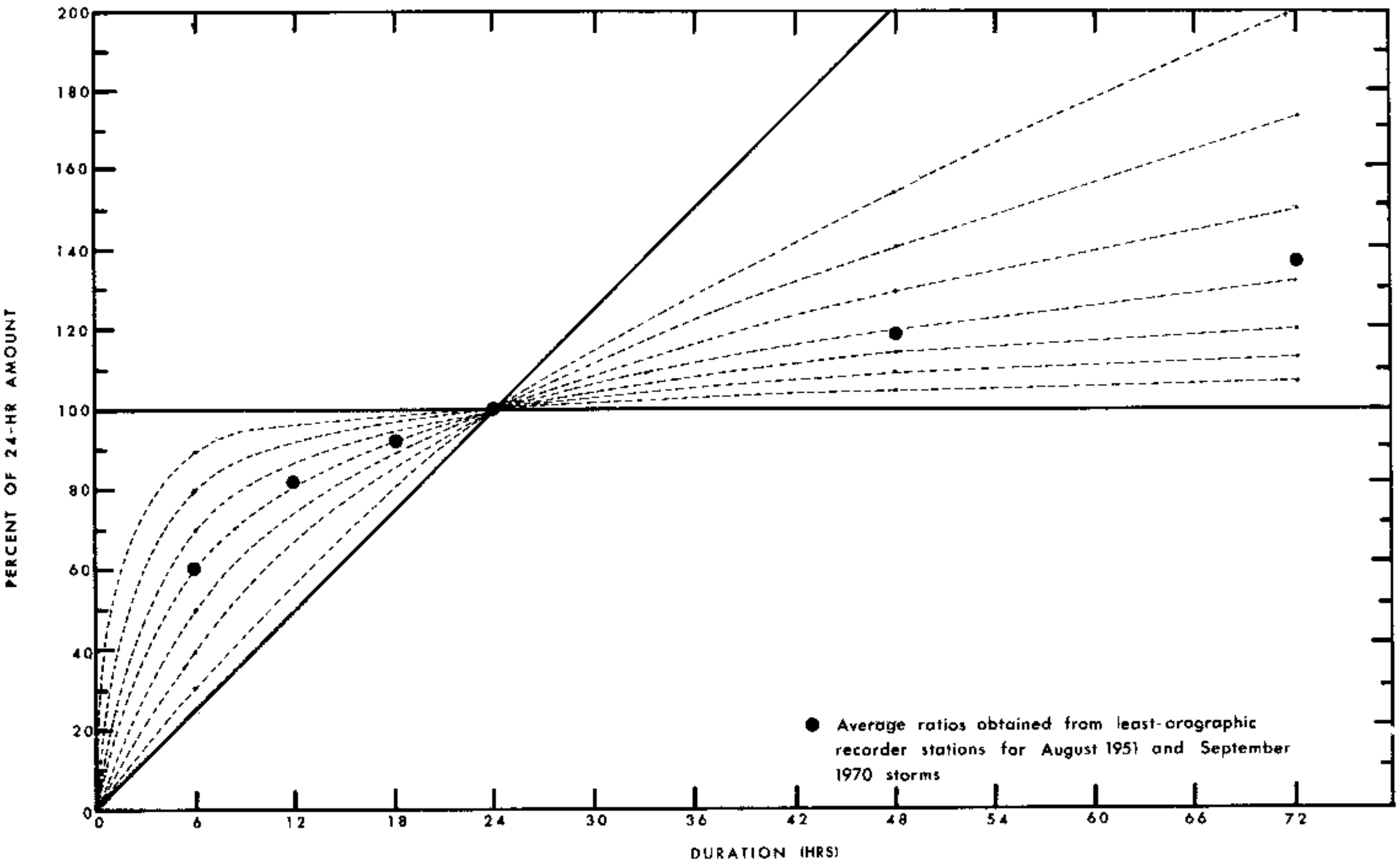


Figure 2.20.--Idealized depth-duration curves in percent of 24-hr amount. For development of this diagram see section 2.4.2. Selected durational values from this diagram are presented in table 2.9 for various 6/24-hr ratios used in figures 2.25 to 2.27.

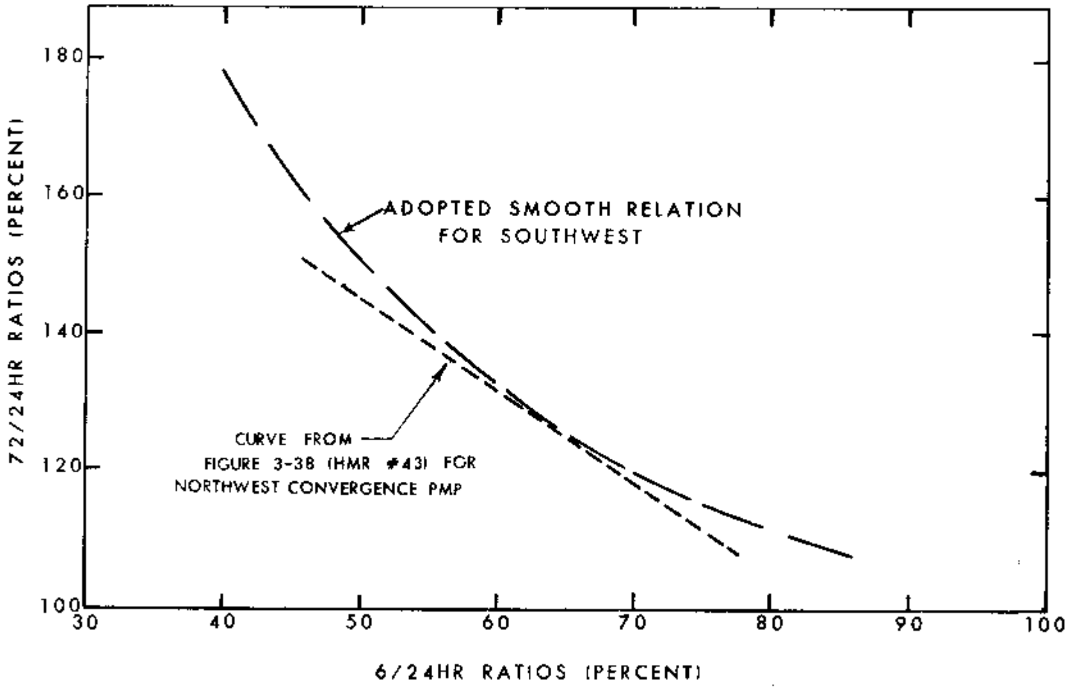


Figure 2.21.--Adopted 6/24-hr vs. 72/24-hr convergence PMP ratios.

next two days. Again, most of the rain during frontal passage was caused by thunderstorms and therefore make this case unrepresentative of a major winter storm. As to the meteorological cause for the other data in figure 2.19, no check was made, but it is believed they tend to support a seasonal distribution in the ratios shown.

The recorder rainfall data for stations in least-orographic areas, table 2.4, were processed to determine monthly average 6/24-hr within-storm ratios for maximum 24-hr rainfalls. This was done by selecting the 20 highest 24-hr rainfalls of record for each month and station and purging to reduce the influence of short term thunderstorm events. The purging was accomplished by eliminating 6/24-hr ratios greater than 0.90. In many instances, particularly during the summer months, fewer than 20 cases were available. From these cases that met the purging criterion, ratios from the five highest 24-hr rainfalls for each station were averaged to obtain mid-month subregional ratios. Some monthly averages had less than five cases. The subregional values are shown on a seasonal plot in figure 2.22. Although there is considerable scatter this may be due to the limited sample. There is a definite trend for higher 6/24-hr ratios in the warm season. These monthly averages are plotted on a seasonal plot, figure 2.23, as short dashes. Four other sets of data have been added to this figure to aid in determining the seasonal variation. Among-storm 6/24-hr ratios (highest monthly 6-hr rainfall divided by the highest monthly 24-hr rainfall) were averaged for 6 stations that were helpful in determining the initial seasonal variation of convergence PMP (fig. 2.4). These are shown by Xs in figure 2.23. A third set of 6/24-hr ratios were monthly averages of station data in the storms listed in table 2.5 along with the August 1951 and September 1970 storm (open circles in fig. 2.23).

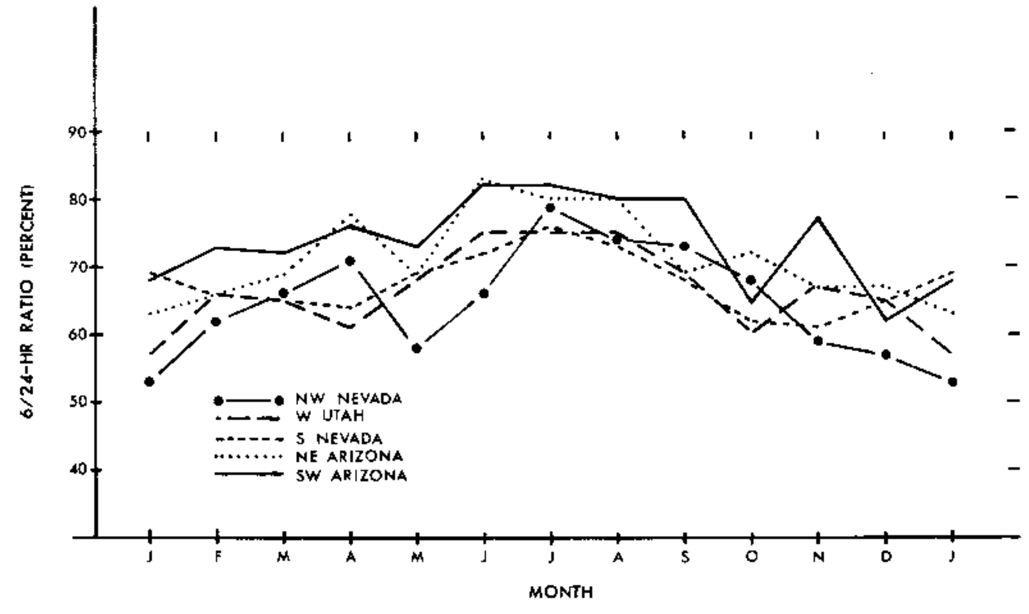


Figure 2.22.--Seasonal variation of 6/24-hr ratios at least-orographic subregion midpoints. Based on averages of station data (table 2.4) for maximum 24-hr rainfalls.

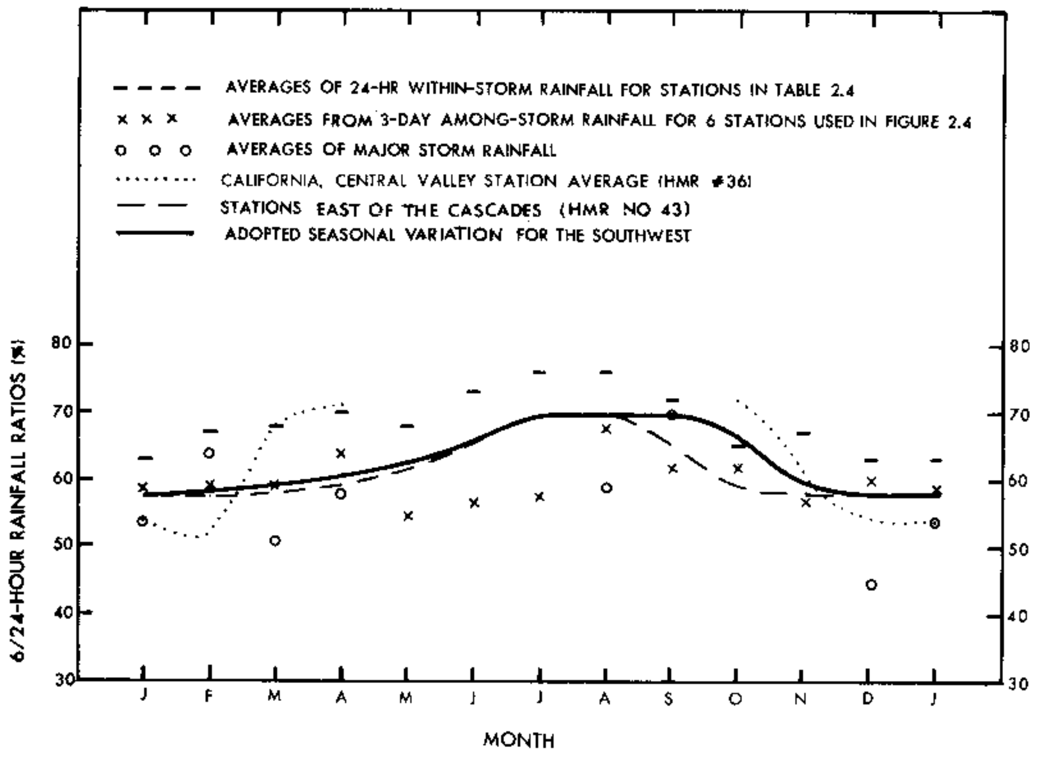


Figure 2.23.--Seasonal variation of 6/24-hr durational rainfall ratios for Southwest and adjacent regions.

No major storm data was available for the months of May, June, July, October, and November. Seasonal variation of 6/24-hr ratios used for convergence PMP in adjoining regions, are also shown in figure 2.23.

We have adopted the mean seasonal variation indicated by the solid curve in figure 2.23. This curve is quite similar to that used in the Northwest. The major difference is an extension of the summary maximum to include September and early October. The occurrence of general tropical storm rainfall, e.g., September 1970 into Utah and the October 1911 into Colorado, this late in the year is the basis for this extension. The smooth adopted curve with highest ratios in summer is generally supported by an average of the Southwest data (dashes, Xs, and open circles).

2.4.4 Regional Variation

The seasonal plots of 6/24-hr ratios for each least-orographic area (fig. 2.22, in addition to higher values in summer, also show some tendency for higher ratios throughout the year for the southern subregions than for the northern subregions. For example, the ratios for southwestern Arizona give the highest ratios for 7 of the months, and only slightly lower ratios than some other area for 3 other months. Ratios for northwestern Nevada are lowest for 6 months and near-lowest for 2 other months. This latitudinal trend in ratios was preserved by using the adopted seasonal variation for all locations from figure 2.23 as a guide in smoothing the curves. Shifting the adopted seasonal variation curve to fit the distribution of 6/24-hr ratios for each region shown in figure 2.22 resulted in a set of smooth curves similar to that shown in figure 2.24. Because the magnitude of the ratios shown in figure 2.22 is somewhat greater than the adopted curve in figure 2.24, the set of smooth regional curves was adjusted downward to center their range about the adopted curve as is shown in figure 2.24.

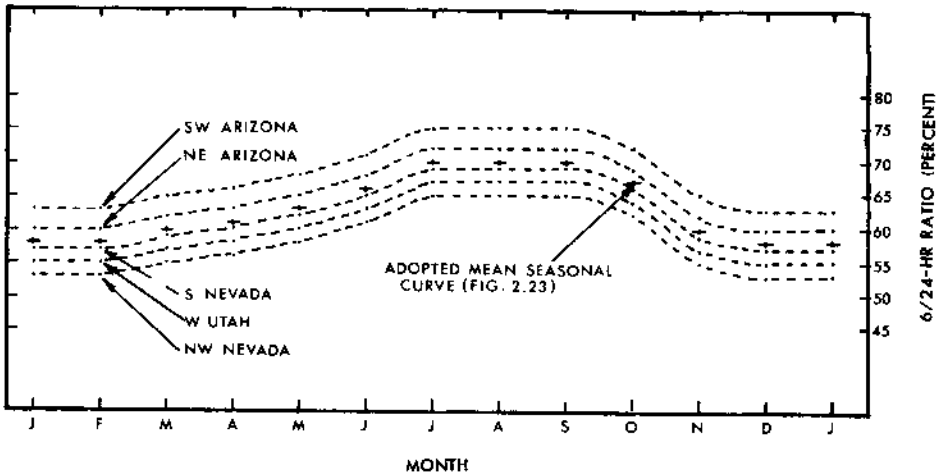


Figure 2.24.--Smoothed variation of 6/24-hr ratios at subregional midpoints.

Ratios from figure 2.24 were plotted at regional centers on a series of monthly maps. Analysis of these data resulted in the monthly maps of regional variation in 6/24-hr ratios shown in figures 2.25 to 2.27. With the exception of magnitude, the analyzed maps show similar patterns.

A comparison between ratios from figures 2.25 to 2.27 and data from HMR No. 43 for a coincident location (42°N, 113°W) is given in table 2.6. Except

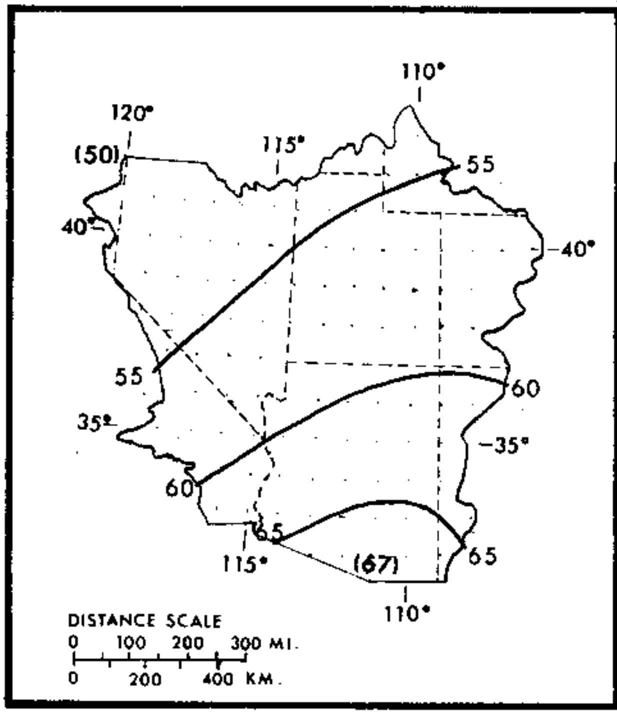
Table 2.6.--Comparison of 6/24-hr ratios in the Northwest and Southwest studies at 42°N, 113°W.

	Month											
	O	N	D	J	F	M	A	M	J	J	A	S
Northwest	.62	.61	.59	.59	.59	.61	.62	.64	.69	-	-	-
Southwest	.62	.55	.54	.54	.54	.55	.57	.59	.62	.66	.66	.66

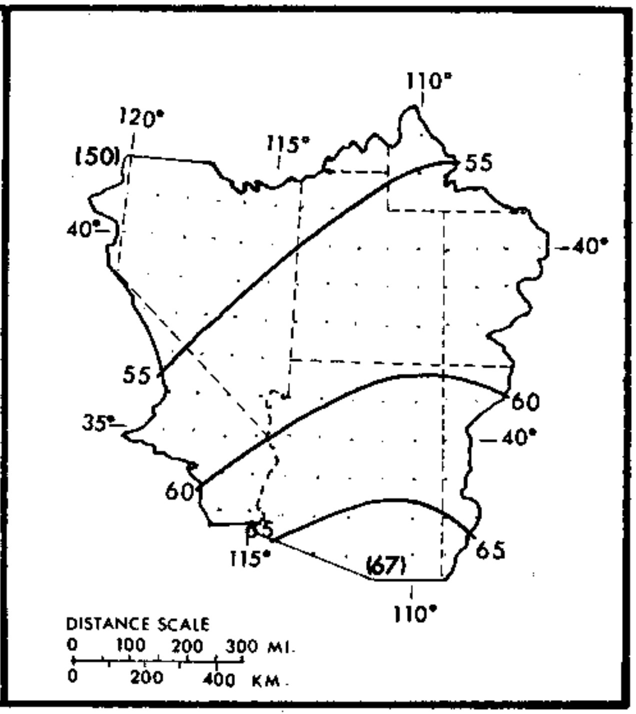
for October, the Southwest ratios are generally about 6% lower than those of the northwest at this location. The larger northwest data ratios are to be expected as they were not purged of bias toward rain showers. Another source of difference results from the difference in development of regional analyses in these two studies. The two studies agree in that the gradient of ratios presented is oriented from high ratios in the southeast to lower ratios in the northwest.

Meteorological support for the pattern of 6/24-hr ratios shown in figures 2.25 to 2.27 comes from the moisture potential in storms. The Sierra Nevada range represents a major barrier to deep moisture flows from the southwest through northwest. Storms that enter the Southwest around the north end of this range are characteristic of cool-season storms of higher latitudes. Major storms that pass south of the Sierra Nevada pick up unstable air from lower latitudes. As the storms continue eastward, additional moist unstable air from over the Pacific is supplied. In terms of 6/24-hr ratios the supply of moist unstable air is shown by higher values, and we believe the more rapid increase in gradient as one passes across the southern portion of the region is realistic.

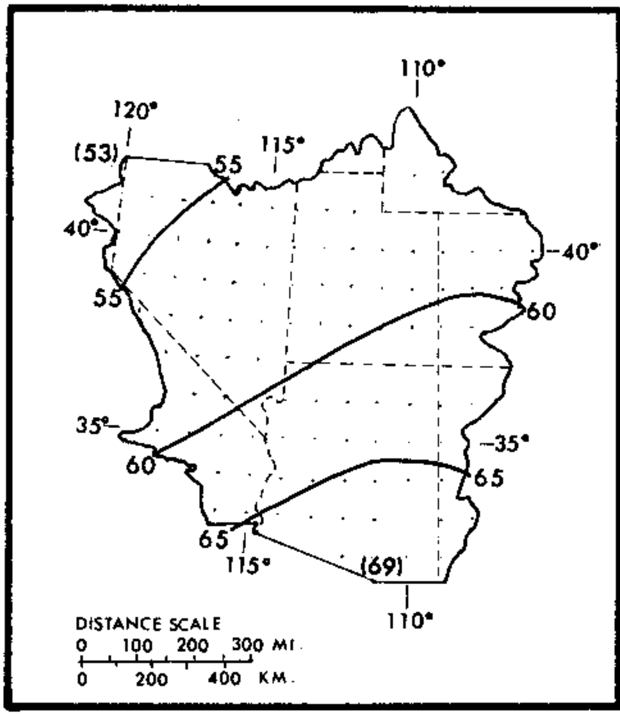
In figures 2.25 to 2.27 the combined seasonal-regional variation in 6/24-hr ratios is evident. These ratios vary between 0.50 and 0.69 during the cool season (Nov. to Mar.) and between 0.59 and 0.79 during the warm season (June to Oct.). Thus, the spread of depth-duration relations applicable to the Southwest convergence PMP is considerably reduced from the possible relations initially developed in figure 2.20. Furthermore, the gradients shown in figures 2.25 to 2.27 imply a greater potential for sustained precipitation in the northern portion of the Southwest than in the southern portion during the summer season. This can be explained as possibly caused by extratropical influences that modify the prototype storm as it penetrates farther inland.



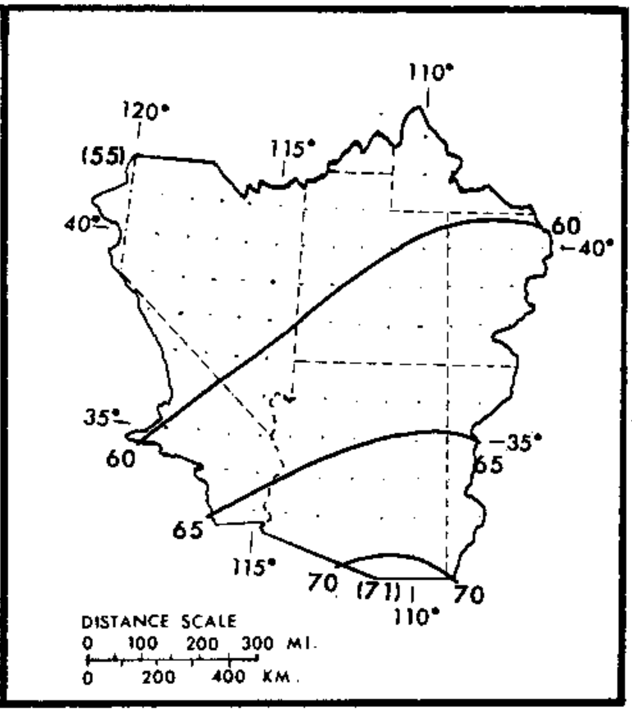
January



February



March



April

Figure 2.25.--Regional variation of 6/24-hr ratios by month (percent). Values in parentheses are limiting values and are to facilitate extrapolation beyond the indicated gradient.

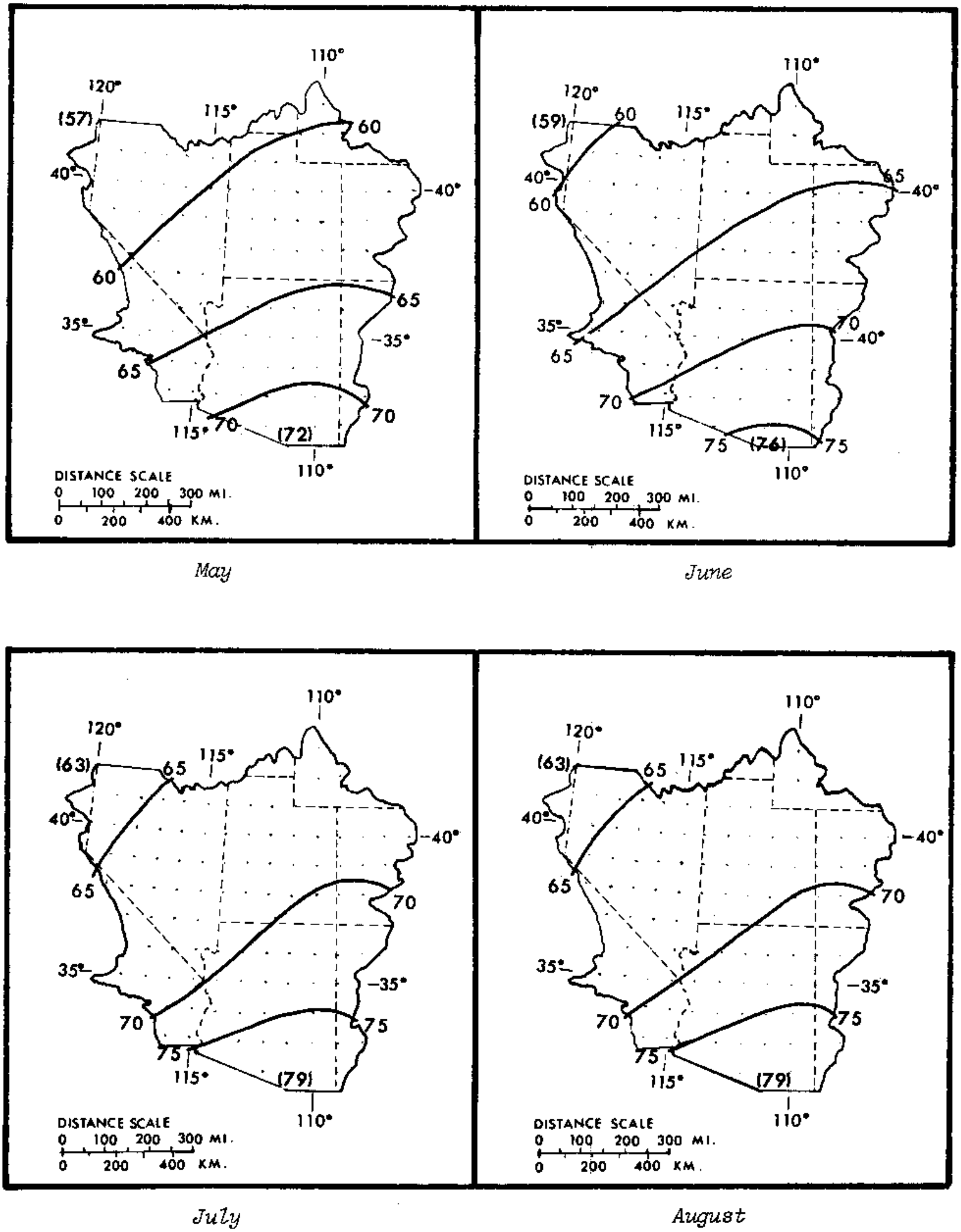
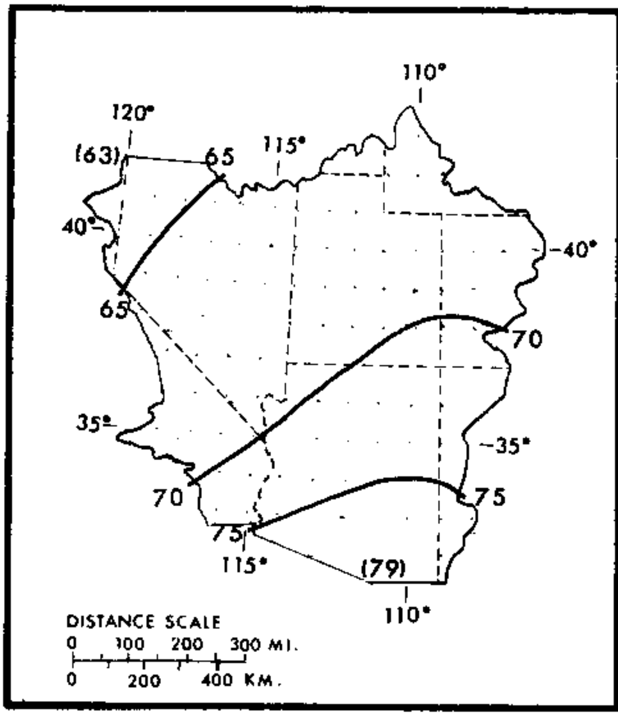
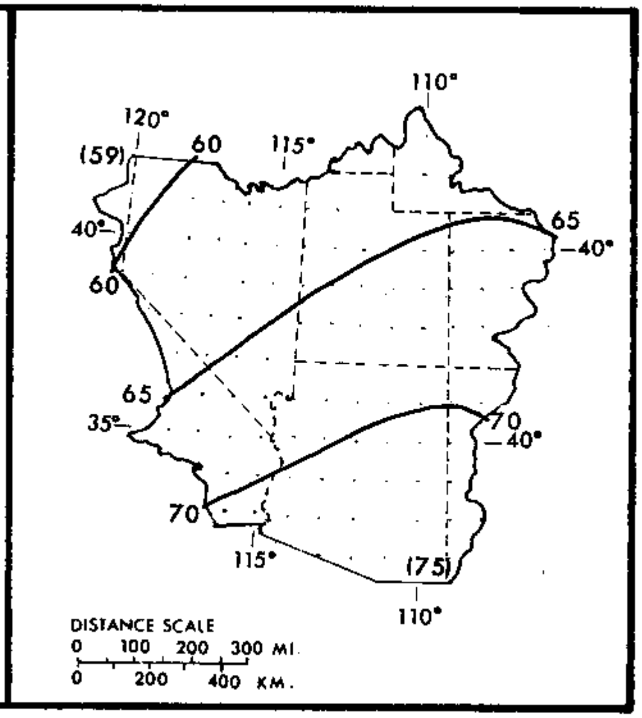


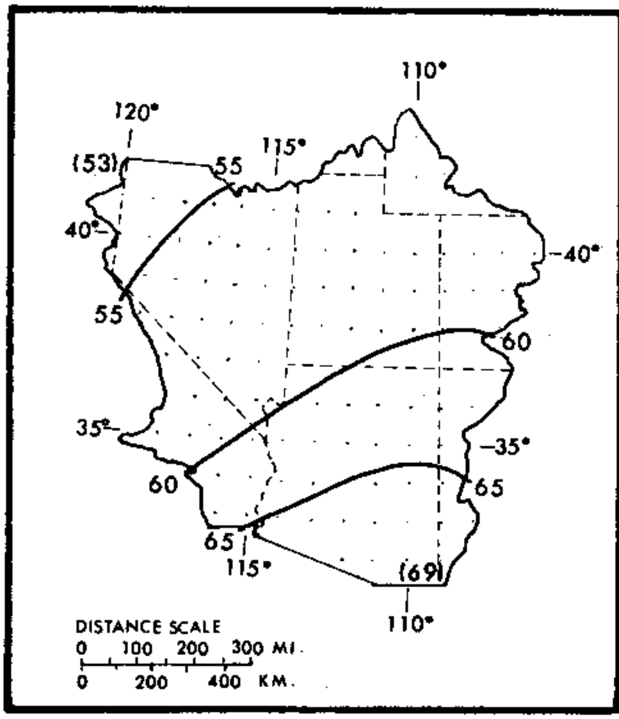
Figure 2.26.--Regional variation of 6/24-hr ratios by month (percent). Values in parentheses are limiting values and are to facilitate extrapolation beyond the indicated gradient.



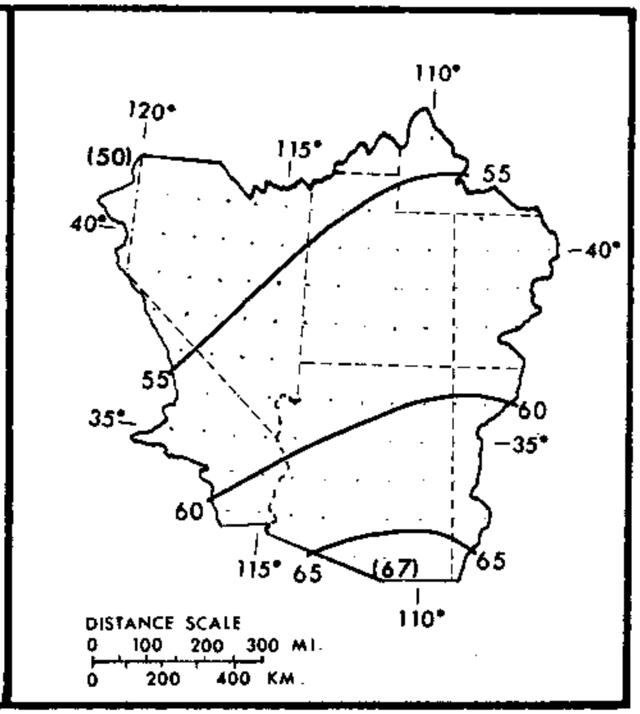
September



October



November



December

Figure 2.27.--Regional variation of 6/24-hr ratios by month (percent). Values in parentheses are limiting values and are to facilitate extrapolation beyond the indicated gradient.

For the range of 6/24-hr ratios included in figures 2.25 to 2.27, depth-duration values in percent of 24-hr amounts are found in table 2.7. The regional ratio maps, and the depth-duration curves presented in figure 2.20 were used in adjusting the major storm data to 24-hr amounts listed in table 2.1.

Table 2.7.--Durational variation of convergence PMP (in percent of 24-hr amount).

Duration (Hrs)					
6	12	18	24	48	72
50	76	90	100	129	150
51	77	90	100	128	148
52	77	90	100	127	146
53	77	91	100	127	144
54	78	91	100	126	142
55	78	91	100	125	140
56	79	91	100	124	138
57	79	92	100	123	137
58	80	92	100	122	135
59	80	92	100	121	134
60	81	92	100	120	132
61	81	92	100	120	131
62	82	93	100	119	129
63	82	93	100	118	128
64	83	93	100	117	126
65	84	93	100	117	125

Duration (Hrs)					
6	12	18	24	48	72
66	84	93	100	116	124
67	85	94	100	116	123
68	85	94	100	115	122
69	86	94	100	115	121
70	87	94	100	114	120
71	87	95	100	114	119
72	88	95	100	113	118
73	88	95	100	113	118
74	89	95	100	112	117
75	89	96	100	112	116
76	90	96	100	111	115
77	90	96	100	110	114
78	91	96	100	110	114
79	92	97	100	109	113
80	92	97	100	109	113

Note: For use, enter first column (6 hr) with 6/24-hr ratio from figures 2.25 to 2.27.

2.5 Areal Reduction for Basin Size

For operational use, basin average values of convergence PMP are needed rather than 10-mi^2 (26-km^2) values. Preferably, the method for reducing 10-mi^2 (26-km^2) values to basin average rainfalls should be derived from depth-area relations of storms in the region. However, all general storms in the region include large proportions ot orographic precipitation.

Our solution was to use generalized depth-area relations developed for PMP estimates within bordering zones in the Central and Eastern United States (Riedel et al. 1956). The smoothed areal variations adopted for the Southwestern States are shown in figures 2.28 and 2.29 for each month or a combination of months where differences are insignificant.

Figures 2.28 and 2.29 give depth-area relations that reduce 10-mi^2 (26-km^2) convergence PMP for basin sizes up to 5,000 mi^2 (12,950 km^2) for each month. Areal variations are given for the 4 greatest (1st to 4th) 6-hr PMP increments. After the 4th increment no reduction for basin size is required. Application of these figures will become clear through consideration of an example of PMP computation in chapter 6.

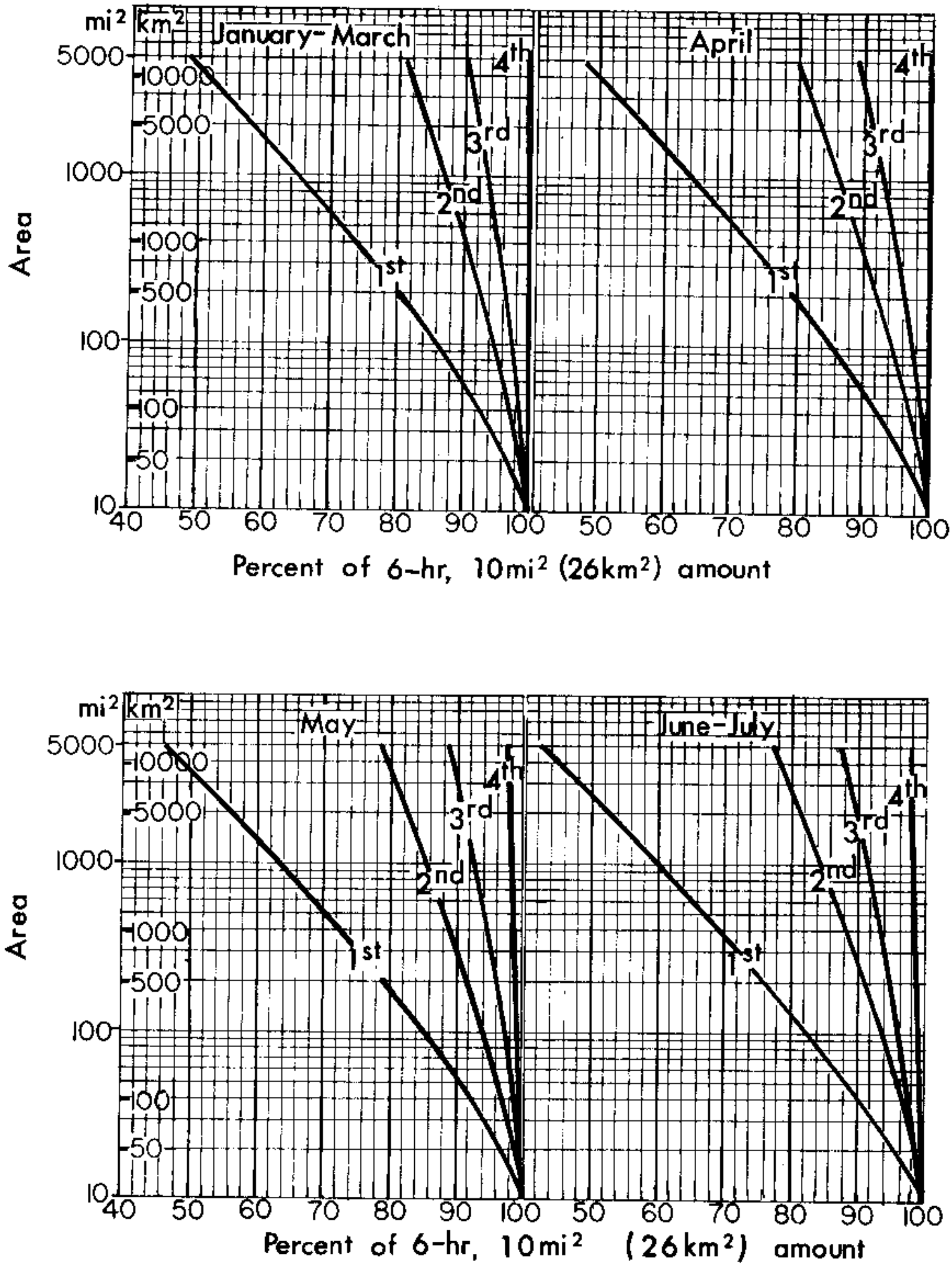


Figure 2.28.--Depth-area variation for convergence PMP for first to fourth 6-hr increments.

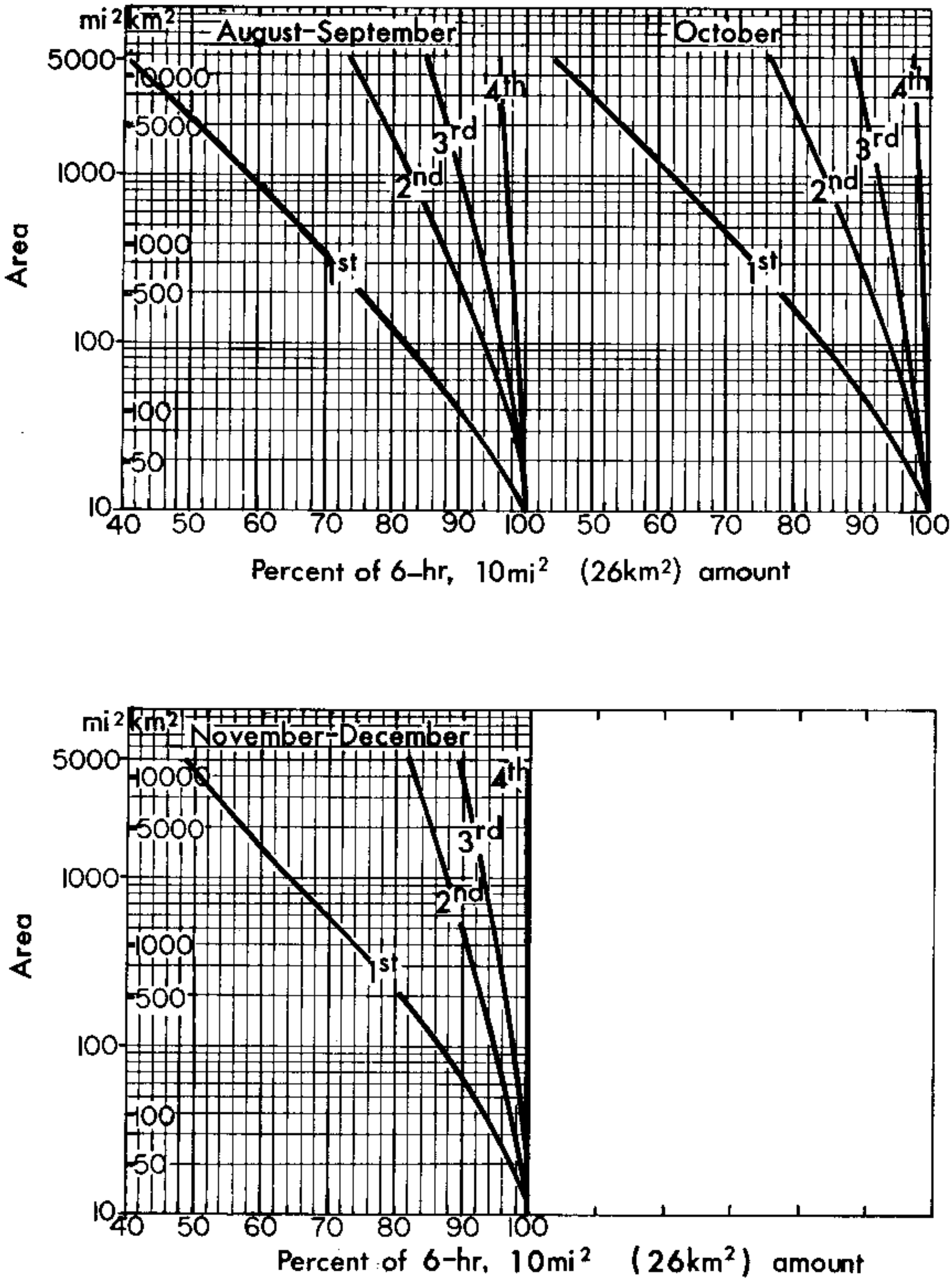


Figure 2.29.--Depth-area variation for convergence PMP for first to fourth 6-hr increments.

3. OROGRAPHIC COMPONENT OF PMP

3.1 Introduction

3.1.1 Methods for Determining Orographic Effects on Rainfall

Recent PMP studies in mountainous terrain have used one of two methods for determining the orographic effects on precipitation magnitude and distribution. One computes precipitation with a numerical orographic windflow model based on physical principles. Examples of the use of this method are HMR No. 36 and HMR No. 43. The other, used where the windflow model does not apply is a more empirical approach in which observed rains on slopes and in nearby least orographic areas (fig. 3.1, see discussion in 3.2.3.2) are compared and the differences are assumed to be orographic. This procedure was used in studies for the Hawaiian Islands (Schwarz 1963), the Yukon River in Alaska (U. S. Weather Bureau 1966b), and the Tennessee River drainage (Schwarz and Helfert 1969).

The western slopes of California mountains (HMR No. 36) are one of the better locations for use of the orographic windflow model for estimating PMP in winter. The Sierras form a barrier to stable moist air. A large number of representative rainfall measurements are available for checking the model. The west slopes of the Cascades (HMR No. 43), are almost as suitable for model calculations but have fewer rainfall measurements. Using the model in the interior of the Northwest, resulted in problems stemming mainly from short mountain ridges and complicated terrain.

In major storms, moisture transport into the Southwestern States involves less stable air than in the Northwestern States and the orographic model with its assumed laminar flow is less applicable. Much rainfall, as in the September 4-6, 1970 storm in Arizona and Colorado, results mainly from an effect called "stimulation" in earlier reports, that is, the initiation of non-laminar convection, including thunderstorms, by mountain slopes.

Because of these factors the orographic windflow model has limited use in estimating PMP for the Southwestern States, where it is more practical to base the estimation of orographic effects primarily on observed variations in precipitation and terrain.

3.1.2 Definition of Orographic Precipitation

In this report orographic precipitation for the general storm is defined as the excess over nonorographic precipitation, and includes stimulation. In this report orographic PMP also includes some local details that were omitted from the smooth convergence PMP index maps.

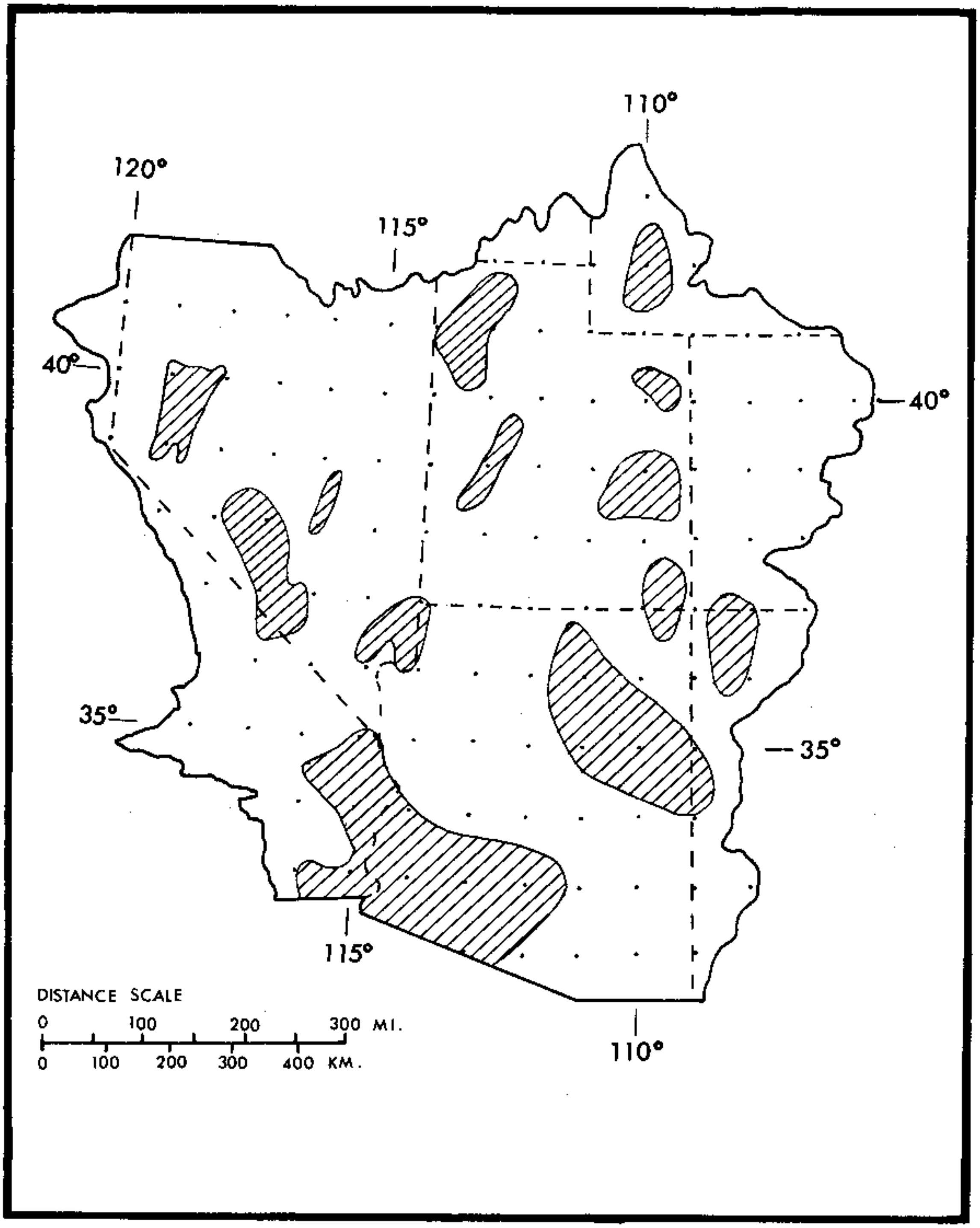


Figure 3.1.--Areas of minimum orographic effects in Southwest States.

3.1.3 Detail in Orographic PMP

Mean annual precipitation (MAP) charts[1] and rainfall frequency maps (Miller et al. 1973) show details quite closely related to terrain. This close a relation to terrain features may not be warranted for PMP. As the magnitude of a storm increases, the energy involved in the dynamic processes also increases and the effect of terrain features is less important.

Inadequate knowledge of the complex mechanisms involved in precipitation in mountainous regions also must be considered. Many of these problems were highlighted in papers presented at a symposium on precipitation in mountainous regions (World Meteorological Organization 1972).

In generalized PMP studies, effects of many wind directions, moisture sources, and storm types must be evaluated. This may be particularly important when small terrain features are considered. Factors pertinent to judging the proper amount of detail follow.

a. A single orographic index map was developed. This is a simplifying step that does not take completely into account differences in terrain effects due to month-to-month variation in moisture, wind, and height of freezing level. Use of a single index map using near highest moisture is a slight maximizing factor.

b. With a condensation level near the surface for the PMP storm, differences between lower and upper reaches of slopes become less than in ordinary storms. This reduces the detailed response to elevation.

c. From several empirical terrain-rainfall studies, discussed later, we concluded that in extrapolation to the general-storm PMP prototype, rainfall is intensified more on large, steep slopes than on smaller, gentler slopes. On the other hand, some regions (with minimum upwind barriers) where conditions are particularly favorable for orographic rainfall, the stimulation of rain at low levels (with a low condensation level in the PMP) may tend to decrease the gradient of rainfall on the slope.

Throughout development of orographic PMP several forms of topographic charts were used to identify primary terrain features. This information was transferred to, and final smoothing made on a 1:2,000,000 scale map. This scale was adopted for the final orographic index map.

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[1]Charts considered were:

a. Normal Annual Precipitation (NAP) for New Mexico (State of New Mexico), Arizona (State of Arizona), Utah (State of Utah), and Colorado (State of Colorado) prepared by National Weather Service, NOAA for data period 1931-1960.

b. NAP for Upper Colorado River drainage (U. S. Geological Survey 1964) for data period 1921-1950.

c. MAP for southeastern Idaho prepared jointly by Soil Conservation Service and U. S. Weather Bureau (1965).

3.2 Orographic Index Map

Rainfall frequency analyses for the Western States have recently been developed by Miller et al. (1973). These analyses were based on multiple correlations relating precipitation to physiographic factors. The resulting charts thus qualitatively show variations that will also be present in the PMP. Following this reasoning, a first approximation of the 24-hr 10-mi^2 (26-km^2) orographic component to PMP was based on an estimate of the orographic component of the 100-yr 24-hr rainfall values.

The first approximation orographic index map was modified by considering a number of other precipitation/terrain effects to arrive at a finalized map. Figure 3.2 is a schematic of the procedure.

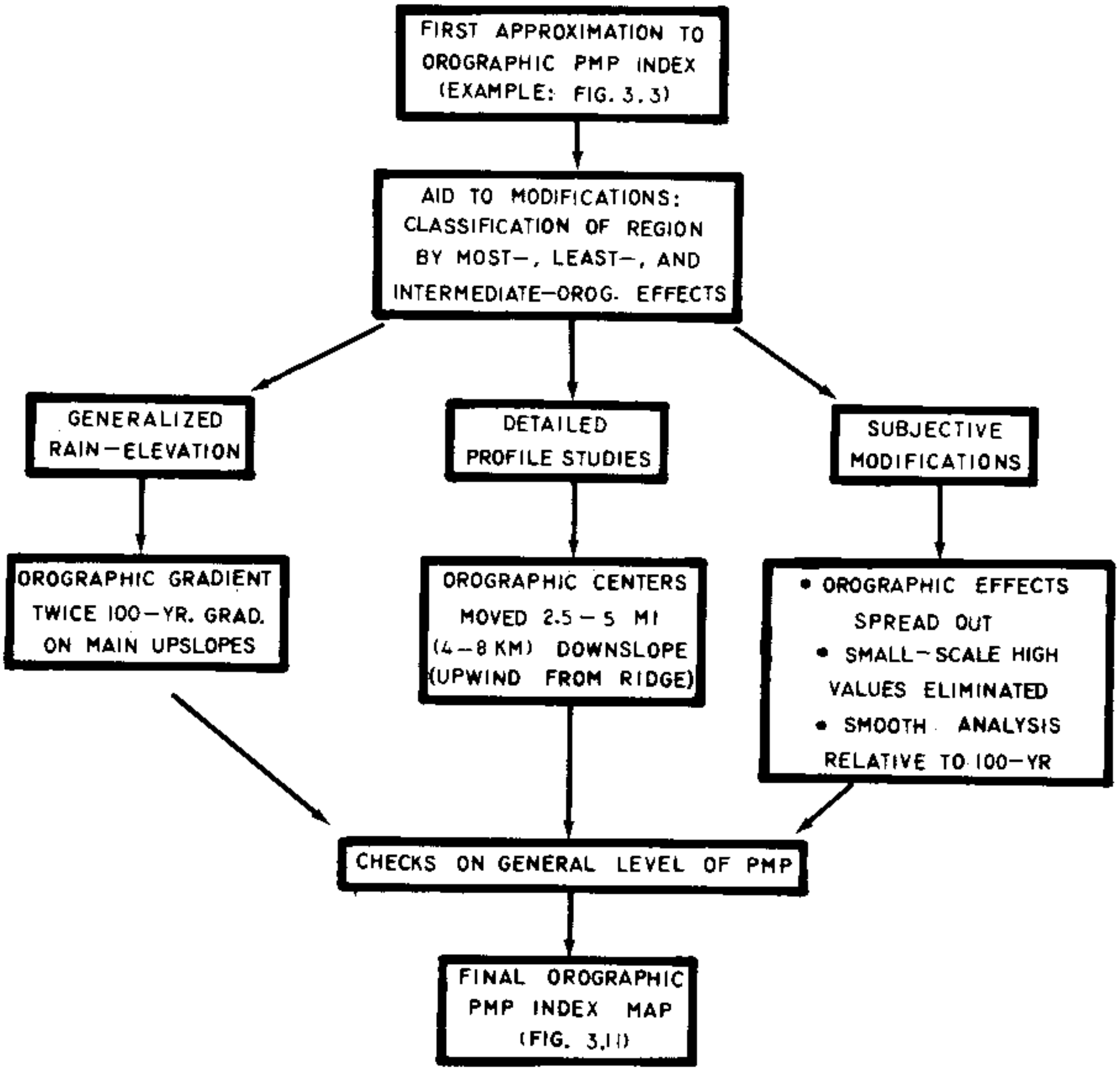

Figure 3.2.--Schematic of orographic PMP index map development.

3.2.1 Development of First Approximation

The 100-yr 24-hr rainfall of 4.0 inches (102 mm) over the nearly flat area of southwestern Arizona and southern California was assumed to be entirely convergence rainfall. Comparable convergence values over the entire Southwestern States were estimated by first applying reductions for effective barrier and elevation[1]. The total 100-yr 24-hr rainfall was then expressed as a percent of this convergence component. These percents (minus 100) are a preliminary approximation to orographic effects.

The convergence component of PMP has been shown to have a regional gradient (See section 2.2.6, and figures 2.5 to 2.16). An adjustment to the preliminary approximation to orographic effects incorporated a regional gradient. For the sake of simplicity, the August 1000-mb (100-kPa) convergence PMP was used as a single index map. This month was selected since a decadent tropical storm is the PMP prototype over much of the region. The preliminary approximation values were multiplied by the convergence PMP values adjusted for effective barrier and elevation. Figure 3.3 shows an example of the first approximation of the orographic PMP for central Arizona.

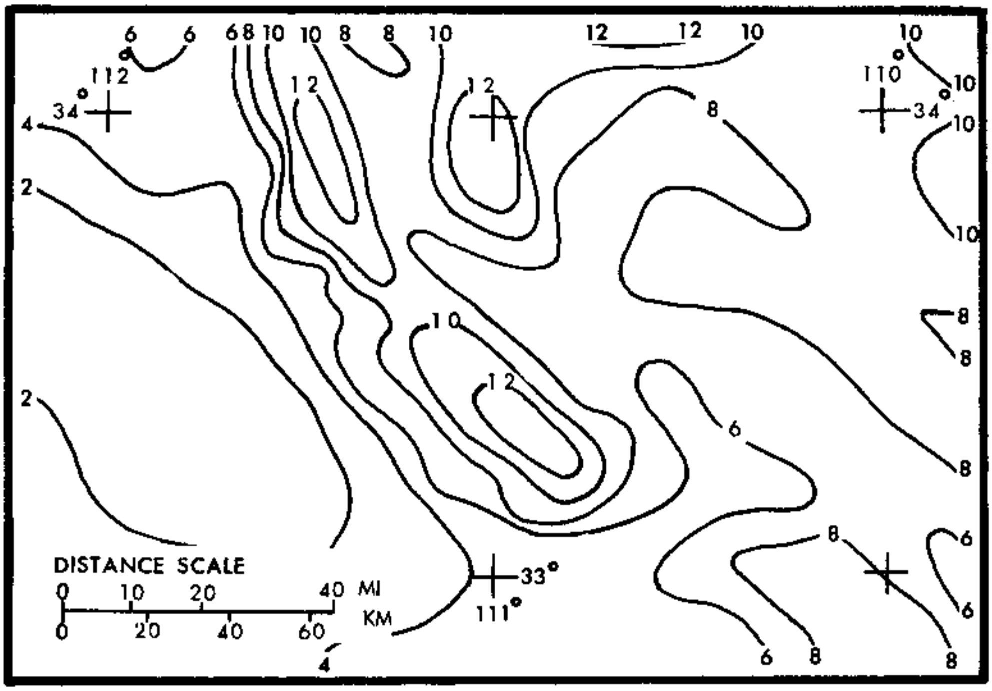

Figure 3.3.--A first approximation to the orographic PMP (inches) for 10 mi^2 (26 km^2) 24 hr in southeast Arizona.

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[1]The effective barrier-elevation chart used was less smooth than the final version shown in figure 2.17.

Implicit in the procedure is the assumption that the orographic and convergence components of PMP have the same relation to each other as the relation between the orographic and convergence components of the 100-yr 24-hr rainfall each appropriately adjusted for elevation and barrier. We have thus estimated the orographic component of PMP utilizing the equation:

$$PMP_o = PMP_c \frac{100\text{-yr}_o}{100\text{-yr}_c}$$

where subscript "o" denotes the orographic component and "c" the convergence component of precipitation. Numerous departures from this assumption were made through modifications discussed in the following sections.

3.2.2 Guidance to Modification

The result of several studies using various data gave guidance to modifying the first approximation to the orographic PMP index.

3.2.2.1. Rain Ratios for Line Segments. We first cover the variations of rainfall along lines or segments across major ridges. Figure 3.4 shows the segments selected for the study region and figure 3.5 shows the segments for Arizona. This last figure also shows the 100-yr 24-hr rainfall. In addition to 100-yr and 2-yr 24-hr values, storm rainfall and normal annual precipitation were considered.

For each of the line segments, we determined the rain ratio or the change in rainfall per 1000 feet (305 m), divided by the low-elevation rainfall. For example, if along a line segment the 100-yr 24-hr rainfall is 2.0 inches (51 mm) at the base and 4.0 inches (102 mm) at the ridge with a 4,000-foot (1,219-m) difference in elevation, the rain ratio is 0.25, or $\frac{4.0-2.0}{4}/2.0$.

This rain ratio is an index of the variation of rainfall with elevation, related to the low-elevation value.

Various rain ratios for this study region and the Northwest States (HMR No. 43) were determined. These ratios are summarized in table 3.1. Rain ratios for the Northwest States in table 3.1a were computed for the orographic PMP index values and 100-yr 24-hr rainfall for various regions with significant orographic effects.

The rain ratios for the segments in figure 3.4 are summarized in table 3.1b, for two rainfall categories; 100-yr 24-hr, and mean annual precipitation. The high 100-yr 24-hr average ratio for southeast California implies low values of rainfall at the beginning point of many of the segments. The large rain ratios from the mean annual precipitation, compared to those for the 100-yr rainfall, are due to the greater frequency of rains at higher elevations. Adjustment of the mean annual precipitation rain ratios for frequency would make them more nearly similar to those for the 100-yr 24-hr rainfall. The comparisons with HMR No. 43 indicate that PMP ratios ought to be larger than 100-yr rain ratios for areas of significant upslope.

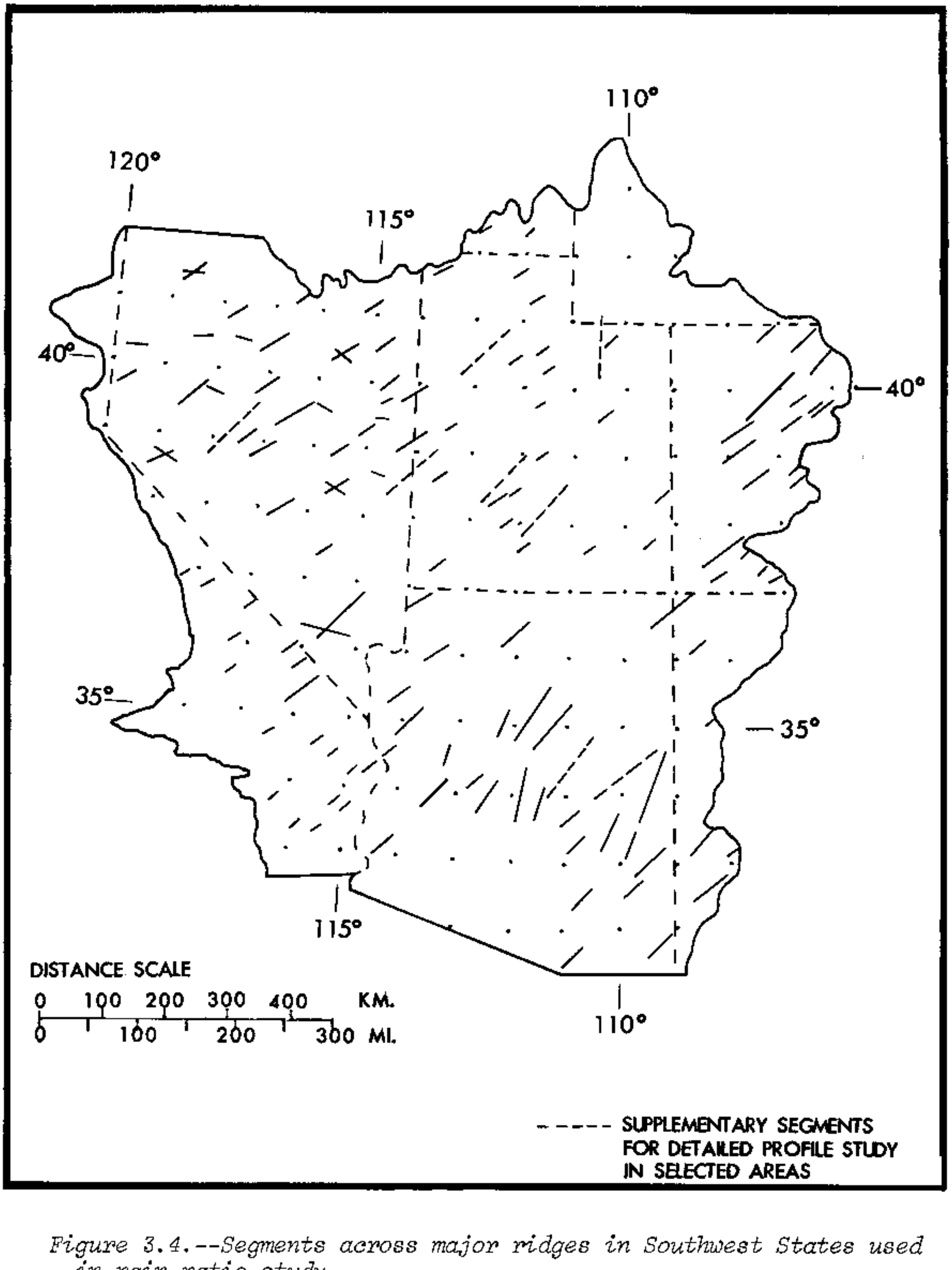


Figure 3.4.--Segments across major ridges in Southwest States used in rain ratio study.

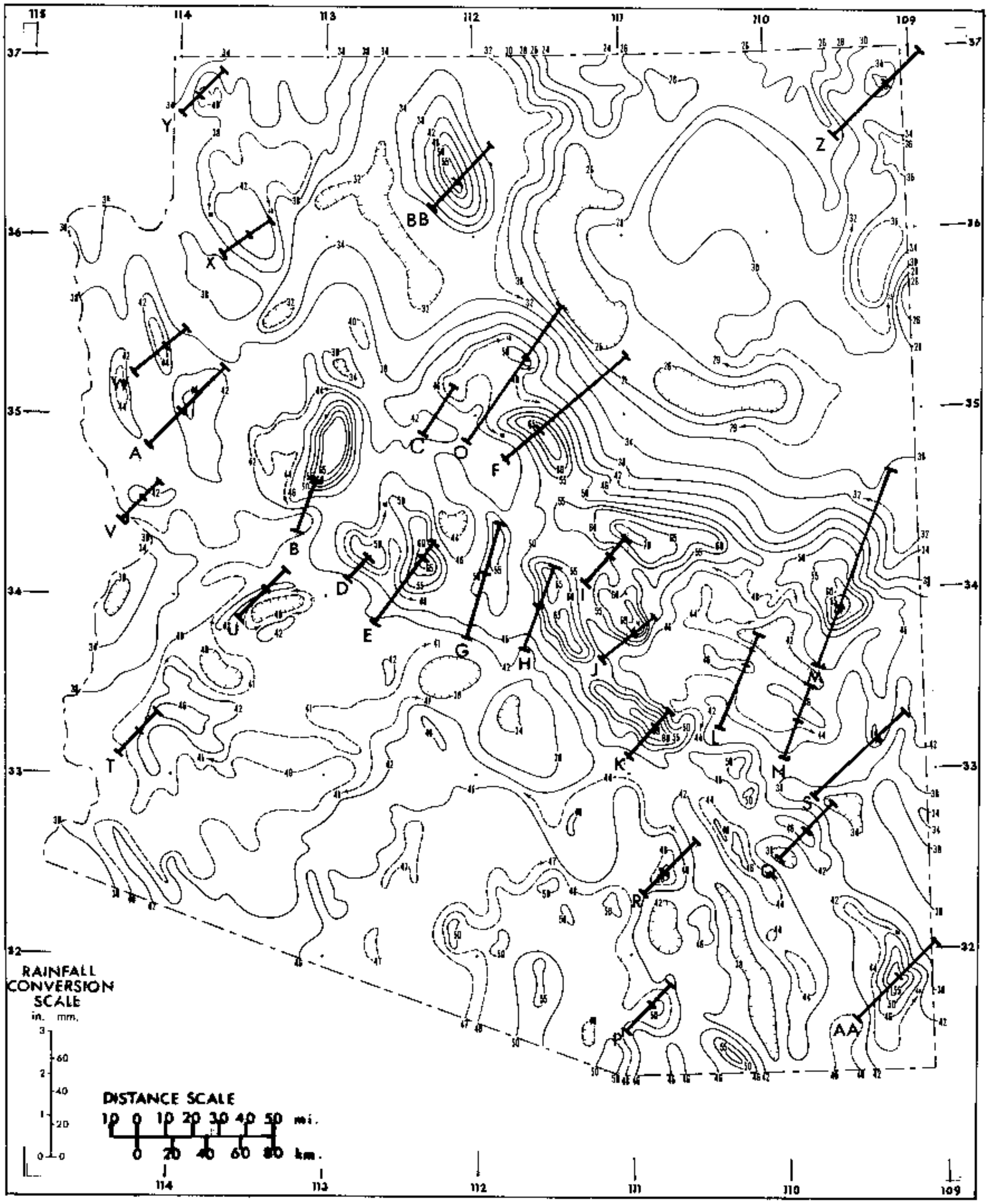


Figure 3.5.--Segments across major ridges in Arizona superimposed on analysis of 100-yr 24-hr precipitation (in tenths of an inch).

3.2.2.2 Rain Ratios for Central Arizona. Other sets of data analyzed were for the prominent slopes north and east of Phoenix. Figure 3.6 is a map of the region with generalized contours and precipitation stations. Figure 3.7 shows the rainfall for these stations during the August 25-30, 1951 and September, 4-6 1970 storms, plotted vs. station elevation. An eye-fitted curve is shown for the August 1951 storm data. If one computes the rain ratio of the curve in figure 3.7, a value of 0.28 is obtained (1.05 in. per 1000 ft/ 3.7 in.)

Rains of one month or longer could be useful for guidance on rain-elevation relations for this same region (fig. 3.6.) We used mean July to September rainfall after adjusting it by a frequency-of-rain vs. elevation relation (not shown). The resulting rain ratio was 0.18, not greatly different from the approximate 0.28 of figure 3.7 for the August 1951 storm and the average rain ratio of 0.21 in table 3.2 for the same storm.

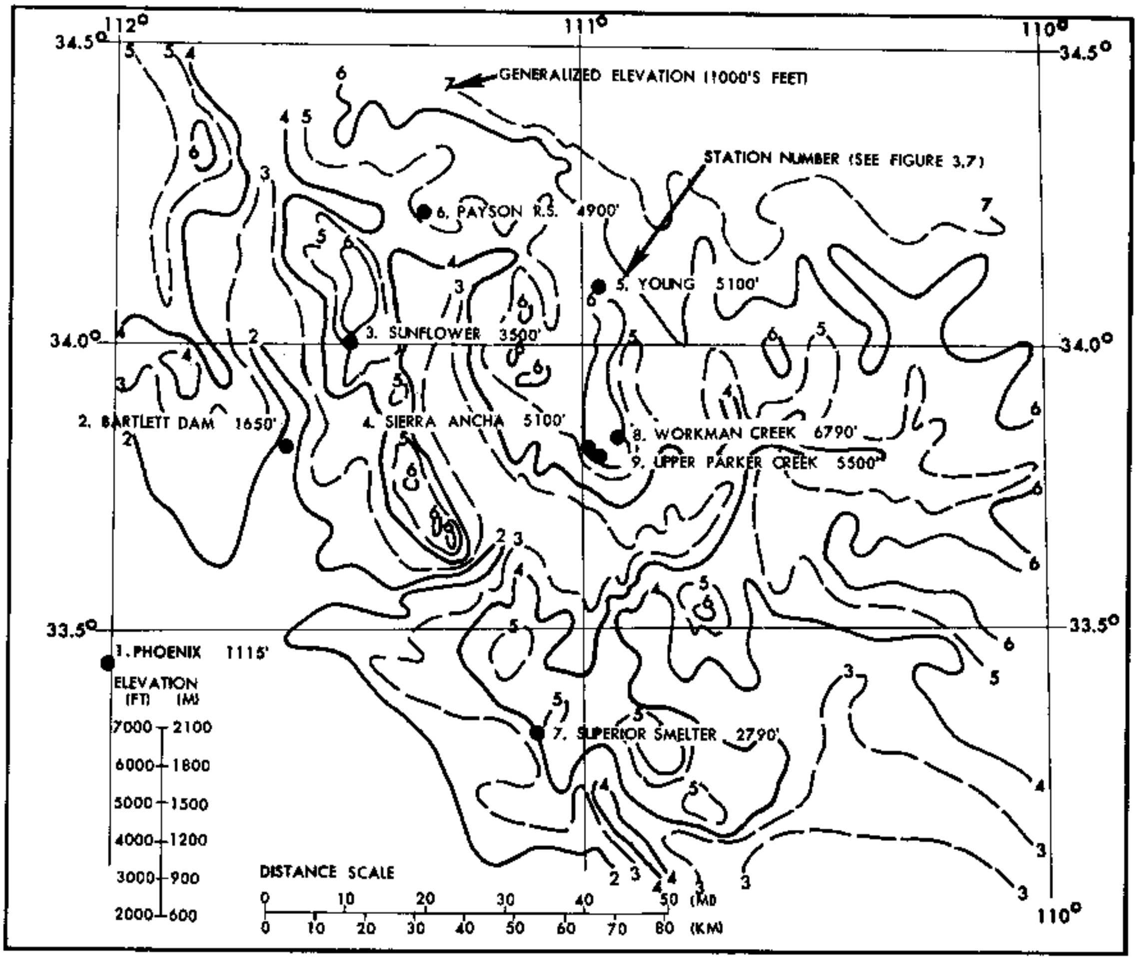


Figure 3.6.--Generalized topography and station locator map in vicinity of Workman Creek, Arizona.

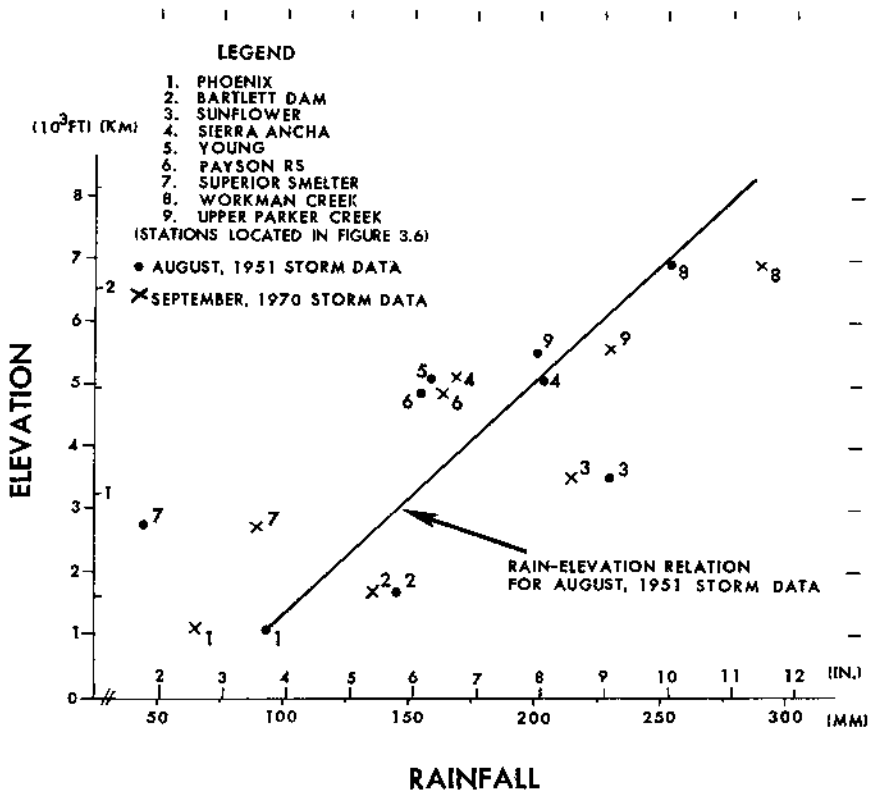
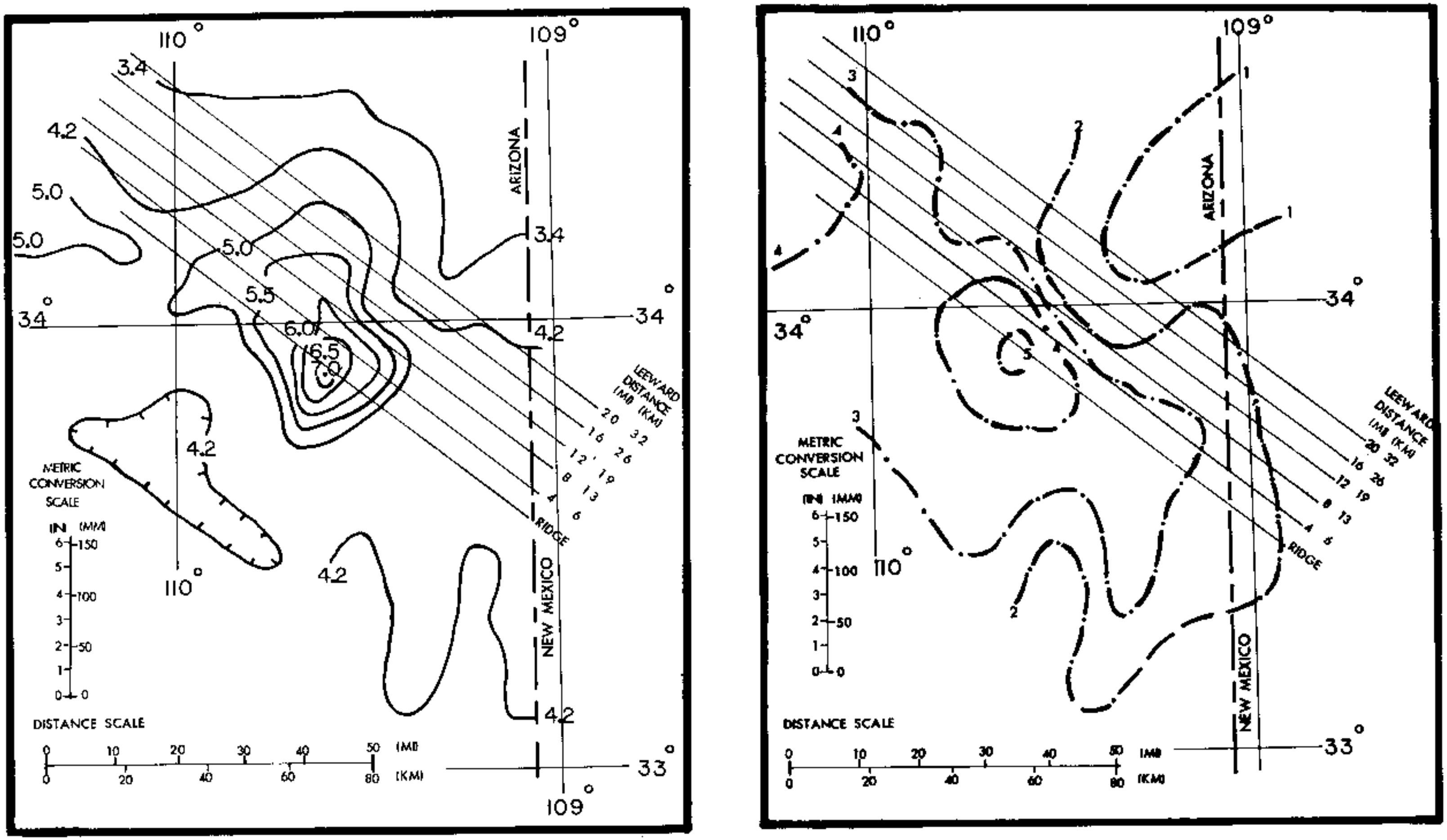


Figure 3.7.--Rainfall-elevation relation for August 1951 storm, and rainfall for September 1970 storm.

For maximum monthly rains in the same region, the variation with elevation is not as closely tied to the frequency of rains. The air in such months would tend to be more nearly saturated at low elevations, (as with the rains for the PMP-type storm), in comparison to mean monthly rainfall cases. With the above in mind, a relation between rain increases and elevation for warm-season maximum monthly rain was developed. These rains give a rain ratio of about 0.19. This appears to give reasonably good agreement with the rain ratio from major storms that are the prototype for the PMP in this portion of the study region.

3.2.2.3 Effects to Lee of Ridges. The decrease of rainfall to the lee of a major ridge in Arizona for each of the two important warm-season PMP-prototype storms of August 1951 and September 1970 was compared to the decrease in the 100-yr 24-hr rainfall. The rainfall along a line through the rainfall centers extending leeward normal to the ridge is the basis for the comparison. Figures 3.8a to 3.8c show the analyzed isohyets and figure 3.9 shows the comparisons.



a. 100-yr 24-hr rainfall

b. August 1951 storm.

Figure 3.8.--Leeward isohyetal patterns.

Table 3.1.--Summary of average rain ratios [change in rainfall per 1000-ft (305-m) elevation difference divided by low-elevation rainfall]

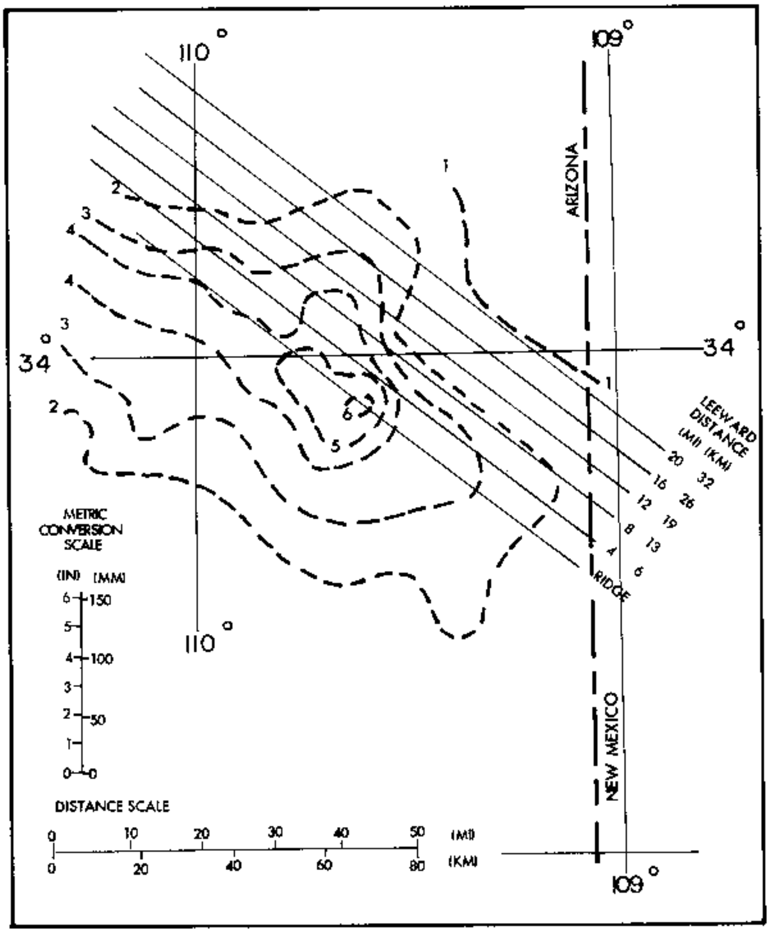
State or portion of State	Average ratio for segments in indicated region for: Mean annual precipitation	100-yr 24-hr	Orog. PMP index (HMR No.43)
a. Northwest States			
Montana (W. of Continental Divide)		.13	.34
Western Washington		.15	.61
Eastern Washington		.21	.47
Southwest Idaho		.09	.82
Northern Idaho		.14	.98
b. Southwest States			
Arizona	.26	.07	
Utah	.46	.10	
Nevada*	--	.12	
Western New Mexico	.56	.10	
Southeast California*	--	.22	
Western Colorado	.39	.12	
Mean	.42	.12	

*The available MAP chart for Nevada did not provide an isohyetal analysis that could be used for computing rain ratios. The southeast California MAP was considered too uncertain in orographic areas for computing reliable ratios.

One other set of rain ratios is shown in table 3.2. This compares the average rain ratios (as previously defined) for 9 selected segments (B, D, E, F, G, H, I, J, K in fig. 3.5) which had considerable rain in the August 1951 and September 1970 storms, with the ratios for the 100-yr 24-hr rainfall. These data show that rainfall from the 2 storms was affected more by the slopes than the 100-yr 24-hr rainfall (rain ratios of 0.31, 0.21 and 0.11, respectively, for the September 4-6, 1970, August 25-30, 1951 and 100-yr 24-hr rainfalls).

Table 3.2.--Average rain ratios for 9 selected upslope segments in Arizona (B, D, E, F, G, H, I, J, K in fig. 3.5).

Source	Ratio
100-yr 24-hr rainfall	.11
August 25-30, 1951 rainfall	.21
September 4-6, 1970 rainfall	.31



c. September 1970 storm.

Figure 3.8.--Leeward isohyetal patterns.

The storm rainfall (both August 1951 and September 1970) decreases more rapidly to the lee than the 100-yr 24-hr rainfall. This result should not be surprising. The 100-yr rainfall is probably made up of isolated storms to the lee of the major ridge. In contrast, the two major storms provided rain over a large region and were associated with inflow from a southerly direction, across the ridge which would decrease the rainfall to the lee.

3.2.2.4 Summary

a. For areas of pronounced orographic uplift, the gradients of PMP should be approximately double that shown by the 100-yr 24-hr precipitation. This is supported by the comparisons of rain ratios of the 100-yr 24-hr precipitation with those of large general storms (table 3.2).

b. To the lee of ridges, PMP should decrease faster with distance than the 100-yr 24-hr rainfall values.

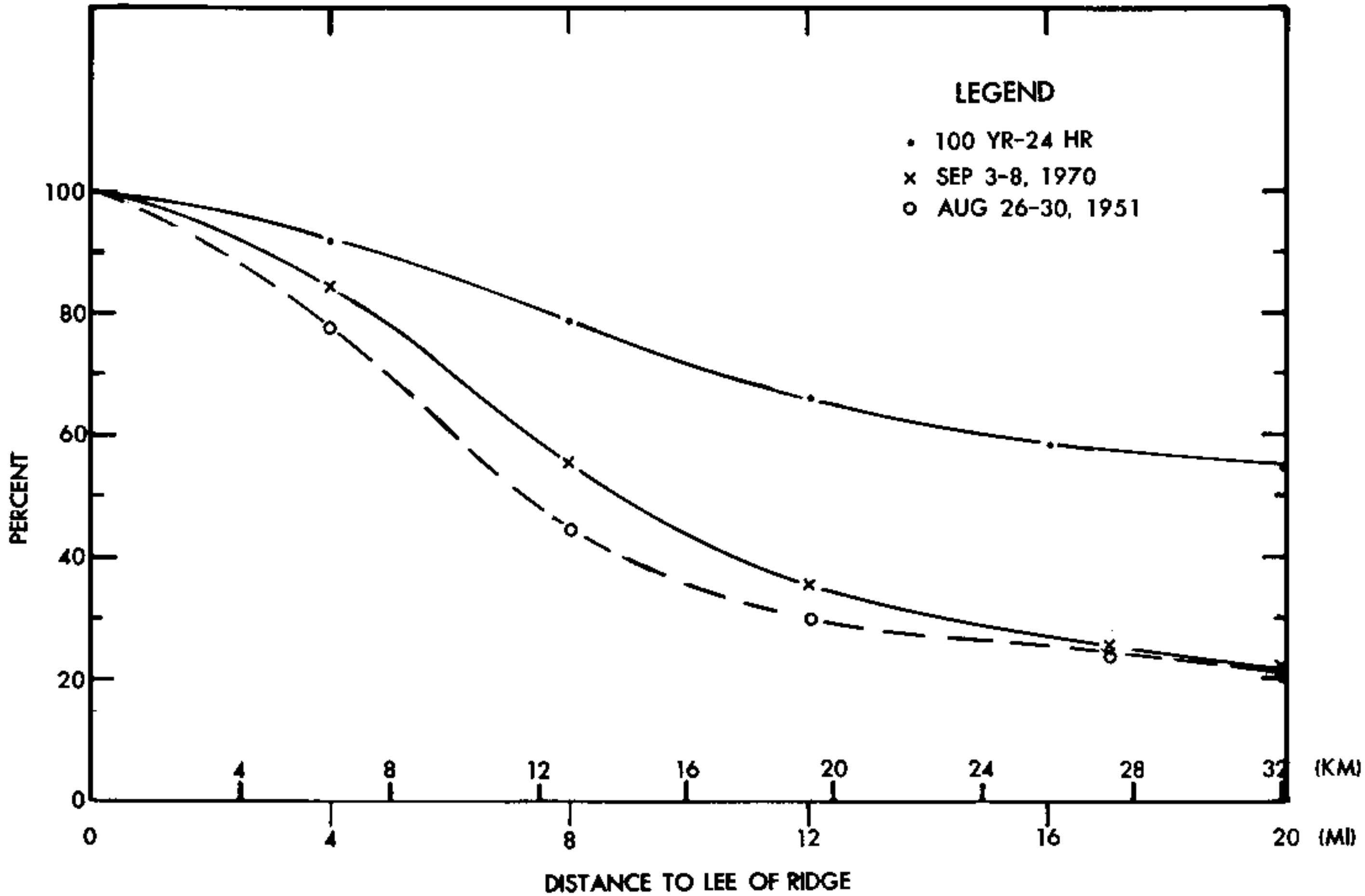


Figure 3.9.--Leeward rainfalls in percent of ridge value for major storms and 100-yr 24-hr rains. Based on fig. 3.8.

The objective procedure of moving the orographic center downslope was also, in some instances, largely negated by the subjective increases for nearby slopes facing differing directions. Maintaining an allowance for stimulation on the lower slopes also tended to negate the initial aim of doubling the upslope gradients of the 100-yr 24-hr precipitation.

3.2.3.2 In Areas of Least-Orographic Effects. A map of least-orographic areas was useful in establishing limits to orographic precipitation gradients, delineating sheltering effects, and providing guidance in modifying the first approximation orographic index map. Figure 3.1[1] integrates the independent interpretation of least-orographic areas by three meteorologists in accord with the following guidelines:

a. Areas where mean annual precipitation was less than 8 inches.

b. Areas where the first approximation to an orographic index map showed less than 10% increase over the convergence component developed for August in chapter 2.

c. Areas where the orographic component of total PMP from the method described in section 5.7 was less than 50% greater than the convergence component.

For the Southwest States a lower limit of 1.0 inch (25 mm) orographic PMP in 24 hours was set in least-orographic regions. Such rainfall in these regions is attributed to either spillover from upwind ridges or to a generalizing (spreading out of the influences of small ridges or hills that make up a part of most areas classified as least-orographic.

Within portions of the outlined least-orographic areas, the threshold of 1.0 inch (25 mm) in 24 hours was increased. For example, rainfall gradients to the lee of upwind ridges at times suggested higher values. In effect, the original areas of least-orographic rainfall, figure 3.1, were decreased in size and their bounds smoothed.

3.2.3.3 In Areas of Intermediate-Orographic Effects. Intermediate orographic areas were those remaining after areas of most- and least-orographic effects were considered. The intermediate areas are usually a mix of nearly flat areas with enough small orographic features to preclude classification as least orographic.

The following factors should be kept in mind in connection with the intermediate areas.

a. With light winds predominating in ordinary rain situations (producing values contributing significantly to MAP charts and lesser values in the series of precipitation amounts used in developing frequency maps), the effect of small orographic features are overly emphasized relative to what one can expect from strong winds in a PMP storm situation.

[1]Note that figure 3.1 differs somewhat from least-orographic regions of figure 2.1. The latter was influenced by availability of station rainfal data.

b. With the varying wind directions possible in PMP storms, orographic effects can be spread out in numerous directions from small areas that act as foci (or stimulation points) for rainfall.

To get away from the overemphasis of orographic effects (point a.), the overall orographic precipitation increase for a particular orographic feature was reduced by 50%. However, a compensating feature stemming from point b. was to spread influences from foci or orographic increases over a larger area. We increased by fourfold the area influenced by small orographic features.

3.2.3.4 Other Modifications

a. Isohyetal peak rainfall centers in the most-orographic regions, covering areas of up to about 100 mi^2 (260 km^2), were eliminated. Most indices of rainfall have a built-in increase with elevation derived from depending too closely on MAP. Where peak MAP values over small areas are supported by data, we feel they must be due to ordinary rains as compared with the strong diversion of air that must take place in major storms.

b. Additional smoothing was done in areas where 100-yr 24-hr rain values were low and had a small range (2.2 to 2.8 inches, 56 to 71 mm). We believe the small range in 100-yr values indicated such smoothing as realistic. This was done regardless of orographic classification.

3.2.4 Modified Orographic PMP Index MAP

Figures 3.11 a, b, c and d are the adopted orographic PMP index maps covering the Southwest States. Figure 3.11a covers the northernmost portion (down to latitude 40°N) while figure 3.11d covers the southernmost portion with figures 3.11b and 3.11c covering the intervening region. The maps overlap by one degree of latitude. This index is for 24 hr 10 mi^2 (26 km^2). Linear interpolation may be used between the isolines for obtaining an average index over a basin. However, within any closed high or low center, the value of the last enclosed isoline should be used.

The remainder of this chapter covers extension of orographic PMP to all 12 months, to durations from 6 to 72 hours and basin sizes from 10 to 5000 mi^2 (26 to 12,950 km^2).

3.3 Seasonal Variation

3.3.1 Introduction

Seasonal variation of PMP is always difficult to define because the rainfall sample is increasingly limited.

For the Western States the problem is especially difficult because of complicated terrain influences which do not permit direct transposition of storms. The approach adopted for the Southwest States was to tie into the seasonal variations of HMR No. 43 and 36 near the boundaries and utilize various rainfall indices within the region.

c. Mean monthly or mean annual precipitation maps exaggerate orographic effects because of a greater frequency of rains at higher elevations. Such maps should be used with caution as guidance to PMP distribution.

3.2.3 Modifications to Index Map

The guidelines summarized above and other aids, were used to modify the first approximation to the orographic PMP index. For such modifications it was expedient to first classify the region into three terrain categories: areas with (1) most- (2) least- and (3) intermediate-orographic effects.

3.2.3.1 In Areas of Most-Orographic Effects. The most important guideline for these areas was to try to make the gradient of total PMP about twice that of the 100-yr 24-hr rainfall. Additional detailed analyses in prominent upslope regions (see example in fig. 3.10) resulted in the rule of moving orographic rainfall centers from 2.5 miles (4.0 km) to 5.0 miles (8.0 km) downslope from the ridgelines. This helped meet the criterion for the gradient of PMP to be twice that of the 100-yr 24-hr rainfall. In some terrain, i.e., where the ridges are small or close together such rules do not apply.

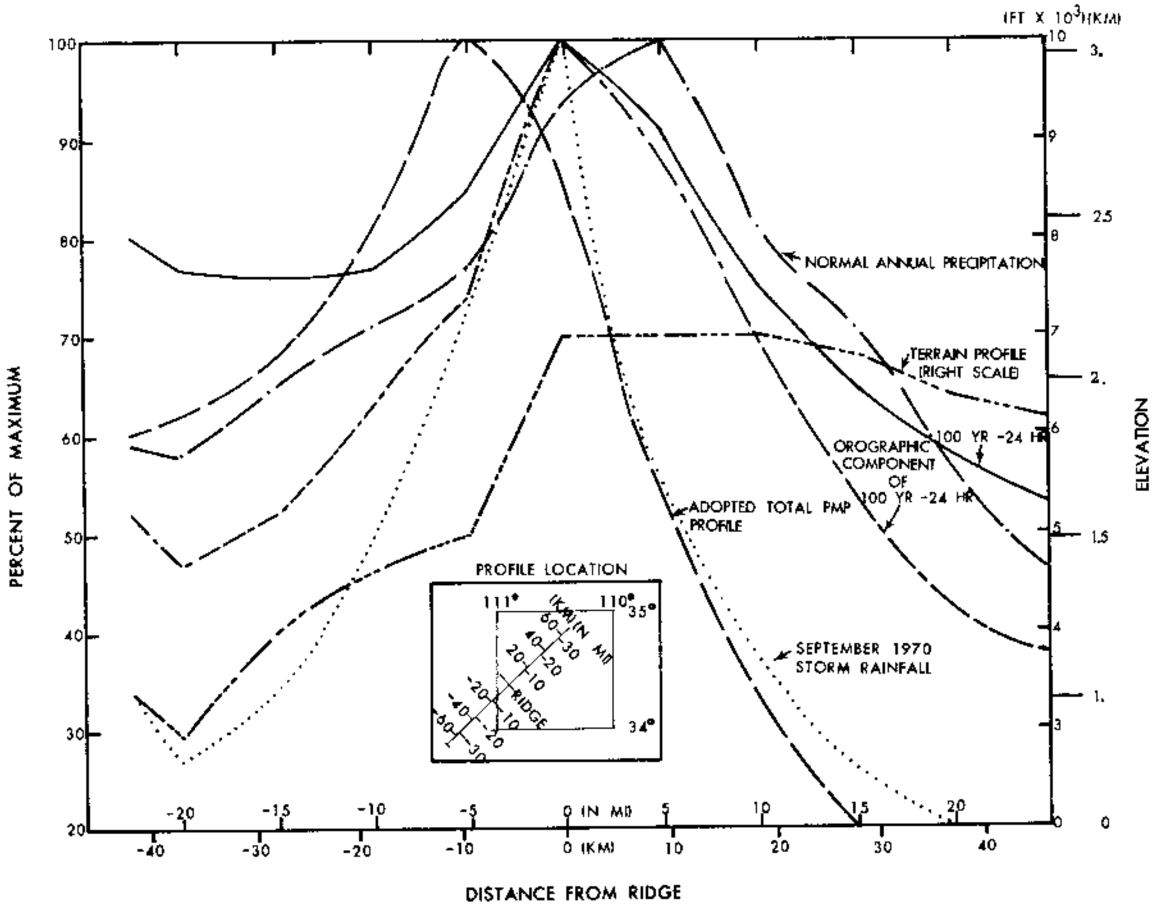


Figure 3.10.--Example of profiles of several rainfall indices (in percent of maximum values).